HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

MATEMAATTIS-LUONNONTIETEELLINEN TIEDEKUNTA
MATEMATISK-NATURVETENSKAPLIGA FAKULTETEN
FACULTY OF SCIENCE

Tiedekunta – Fakultet – Faculty Faculty of Science	Koulutusohjelma – Utbildningsprogram – Degree programme Atmospheric Sciences

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Työn nimi – Arbetets titel – Title
Reconstruction of the past 3000 years of vegetation and land-use dynamics: a case study of pollen and geochemical indicators of Lake Lavijärvi in the Karelian Russia

Työn laji – Arbetets art – Level	Aika – Datum – Month and year	Sivumäärä – Sidoantal – Number of pages
Master's Thesis	09/2018	61

Tiivistelmä – Referat – Abstract
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Avainsanat – Nyckelord – Keywords
Paleoecology, Paleoclimatology, Pollen Analysis, Geochemical Analysis, Land-use history, Climate reconstruction, Vegetation changes

Säilytyspaikka – Förvaringställe – Where deposited
University of Helsinki, Faculty of Science, Department of Atmospheric Sciences

Muita tietoja – Övriga uppgifter – Additional information
The thesis is a collaboration between University of Helsinki and Eawag Institute in Zurich, supervised by Prof. Nathalie Dubois at Eawag

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Master's Thesis

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In collaboration with Eawag, Switzerland

Summer 2018

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Chapter 1: Introduction

1.1. The study of Paleoclimate and its significance

Paleoclimatology is the study of past climate using different proxies and data in order to reconstruct the earth's climate history. The key to understand present climate patterns and how they will evolve through time all lie within understanding how climate used to be in the past and how abrupt changes happened. Various natural archives exist to evaluate past climate, such as ice cores, tree rings, or sediment cores. Biological microfossils (e.g., diatoms) and pollen grains that are deposited in sediment cores can be named as major proxies that yield valuable information about earth's climate history. A climate proxy is a natural indicator that has the imprints of past climate conditions and chemical features that can be measured directly. These measurements can lead to more precise reconstruction of climate conditions over long periods of time in earth's history ("what are "proxy" data?", www1).

Reconstruction of past climate using microfossil proxies has contributed to providing important insights to the natural variability of climate in late Holocene period. The late Holocene period which has started around 5000 years ago is a period of considerably stable climate condition compared to glacial-interglacial cycles. Globally, this period presents the change in the pattern of solar energy distribution, which caused weakening of the monsoon systems in Africa and Asia and hence brought on more dryness. These changes were also accompanied by summer time cooling temperatures in the northern hemisphere (Wanner et al. 2008). Advances in the range of mountain glaciers in the northern hemisphere such as in the European Alps or in Scandinavia are among the climate features of the late Holocene. This has most probably resulted from the Little Ice Age between the 14th and 19th centuries, "when the lower summer insolation in the northern hemisphere, due to orbital forcing, coincided with solar activity minima and several strong tropical volcanic eruptions" and caused severe cooling effects (Wanner et al. 2008). During the late Holocene, , in the upper north hemisphere such as southern Finland and Russian Karelia, the cooling of temperature is more visible. Generally, the trend of climate is characterized by warm and moist in mid Holocene and cool and moist during the late Holocene. The lakes water depths around southern Finland increased progressively during the late Holocene and thus explain the inclining moisture levels (Luoto et al. 2010; Seppä and Birks, 2001). From 3000 cal BP (Before Present) to now after the Holocene thermal maximum, the climate adopted a pattern of gradual cooling down. Except for the warm and dry medieval climate anomaly, the climate of late Holocene in this area mainly experienced cooling events such as the Little Ice Age that occurred between ca. 1050 to 650 BP and 400 to 200 BP, respectively (Luoto, 2009).

Paleoclimatic data can provide crucial information regarding the pattern of climatic shifts and adverse changes that took over the ecological habitats. Such minor to drastic changes in climate can results in alteration of certain climatic thresholds. For instance, a climatic abnormality that could have been tolerated by the environment at certain ages, could now be a tipping point for a major climatic shift. If other natural incidents such as a volcano eruption simultaneously influence the environment, the impact of these abrupt climatic changes can become more severe (Overpeck and Cole, 2006). Thus, the study of paleoclimate to find out the climate evolution and fluctuations throughout history is emphasized for the purpose of recognizing future climatic shifts, rates of these changes and the environmental responses and tolerations to such alterations. Paleoclimate data, especially numerical statistics derived from the paleoclimatic proxies can help generate climate models. Though these models still hold uncertainties as they are based on fossil data and can't be examined with the accuracy of instrumental data, they are still quite helpful if studied carefully to help develop stronger tools and theories to detect future climate variations (Hansen et al. 2016).

In addition, paleoclimate data are used to evaluate and assess climate models. Paleoclimate data provides temporally long scale and unique information about the large-scale patterns of past climate changes. The comparison between these changes and current climate models can bring in new insights regarding the sensitivity and tolerance of biosphere to the changes in atmospheric composition. These assessments can provide valuable simulations and reliable estimates about the current and future climate change (Braconnot et al. 2012). Thus, paleoclimate information can be used to test climate models and help improve the efficiency of such models.

The continuously growing climate change issues and debates has put an emphasis on investigating causes of this change. This has resulted in further interest to study past climate patterns and fluctuations as a way to figure out current and future climatic variations and possible transitions.

1.2. Using pollen analysis for paleoclimatic reconstructions

Pollen grains are the male gametophyte of all flowering and cone-bearing plants (Hormaza and Herrero, 1996). They are known as one of the strongest proxies of nature. Palynology or pollen analysis is the study of pollen grains in order to detect current or past vegetation cover. This analysis can be made for several purposes. Among them is the study of pollen grains for reconstruction of past climate.

Pollen grains are usually dispersed seasonally. This can be subject to change if for instance there is an abnormal weather condition such as an extreme harsh winter. When dispersed, pollen grains depending on their weight, shape and other physical features, travel or land on various surfaces. They can get deposited and preserved right away if they land on solid ground and do not get blown away. Commonly, pollen grains from the surrounding catchments of lakes are transported by wind or rivers and settle after some distance, again, depending on how long they can be suspended. They are then preserved in sediments over geological timescales.

Plants, trees and all vegetation types, especially their geographical distribution are greatly subject to the influence of climate and meteorological variations. Every plant has its own resilience level against different extreme climatic conditions. Each one of these plants has a special favorable temperature or requires different amount of moisture for optimal photosynthesis. Thus, all plants can have a unique behavior when faced with harsh weather conditions.

Therefore, changes in past climate would have affected the precedent vegetation patterns. In this manner, studying the archive of fossil pollen recorded in lake sediments, can lead to reconstruction of past vegetation and subsequently the climate conditions. Nonetheless, one should bear in mind that all plants produce different kind of pollen and therefore each pollen type has an exclusive production, dispersion and preservation pattern. In this regard, to understand the variations of pollen in the past, we should comprehend the relationship between modern pollen taxa and climate conditions and then apply this knowledge to reconstruct the old vegetation variations. Figure 1 shows a synthetic diagram that illustrates the correlation between paleoclimate data and fossil pollen and how palynology helps understanding the climate patterns.

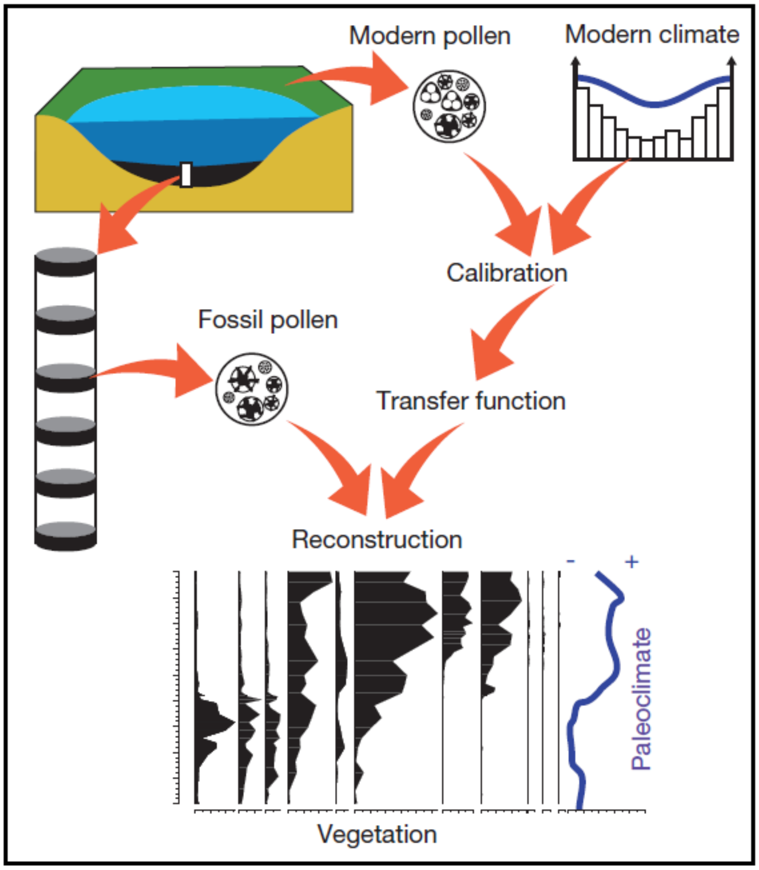

Figure 1: Synthetic diagram developed by Juggins in an unpublished paper showing steps of climate reconstruction using pollen proxies (Brewer et al. 2007)

Pollen grains are among the most resilient proxies in nature since the hard outer wall of these indicators make them resistant to destruction by many types of harsh environmental conditions such as forest fires and long glacial periods. Hence, in the current age, palynology has become a practical method to use for paleoclimatic reconstructions.

1.3. Research questions and aim of this study

Paleofarm Project

The succession of civilization and the ever-growing need of humans for farming and cultivation has been on the rise over the last millennia. This demand for further agricultural products has resulted in more lands going under cultivation. Deforestation on its own brings about a significant amount of soil erosion. The emptied spaces as the result of deforestations bring on agricultural and pastural activities and they contribute to more soil degradation. In the Paleofarm project, the aim is to study the beginning of land use and human cultivation and farming in certain areas with emphasis on soil erosion rates. The study includes analyzing three different limnological sediment cores from Russia, Greenland and Switzerland. The lakes investigated are known for distinctive human activity in their catchments.

This Thesis

In this dissertation, the focus will be on the pollen analysis and environmental reconstruction of Lake Lavijärvi, one of the aforementioned lakes in Russia and to identify periods of human pressure. The examination of Lake Lavijärvi's pollen records will yield valuable information regarding the past vegetation of the surrounding of the lake and hence provide relevant information about the conditions of the soil in which the plants grew. The study of past vegetation will be key to reconstruct the past climate in this specific timeframe. Evaluating this relationship between vegetation and climate will be beneficial to understand the impact of climate variations on the plants.

Therefore, this thesis will try to answer queries concerning the types of vegetation in the catchment of Lake Lavijärvi in a specific temporal scale and subsequently reconstruct the climate condition of the site. Such questions are namely, 1. What were the main types of vegetation surrounding Lake Lavijärvi? 2. How did these plants and trees change over time? 3. What changes impacted the vegetation? 4. How did the development of these vegetation types affect their environment? 5. And lastly what was the major climate condition during this period?

The Site

The study area is located in western Russia, in the Republic of Karelia. Lake Lavijärvi extends from 61º37′N to 61º38′N and from 30º29′E to 30º31′E with a surface area of 2.01 km^2 and catchment area of 74 km^2. Lake Lavijärvi is among the subsidiary lakes that are sourced from Lake Ladoga which is located on its southeast. Lake Lavijärvi is most probably of glacial origins (Filatov et al. 2007), meaning it was formed in subsidence lands in between moraine ridges and hills. The Karelian Russia and eastern Finland represent today the middle boreal forest vegetation zone. The Geology of Karelia indicates that this area is of the Archaean or Paleoproterozoic Eon and is dated up to 3.4 billion years ago. It represents the largest contiguous Archaean outcrop in Europe.
The current general surroundings of the lake are boreal forests with pines and spruces dominating the area. The area to the northwest of Lake Ladoga, where Lake Lavijärvi is situated, has notably diverse nature. Abundant flora and a rough surface topography are among the various characteristics of this site. In the 20th century, the slash and burn cultivation was replaced by arable field cultivations (Alenius et al. 2004).

The climate of Lake Ladoga and Lavijärvi is temperate continental that is also moderately impacted by the marine currents. Short cool summers, mild winters, noticeable cloud cover and unstable weather conditions throughout the year are among the climate characteristics of this area.

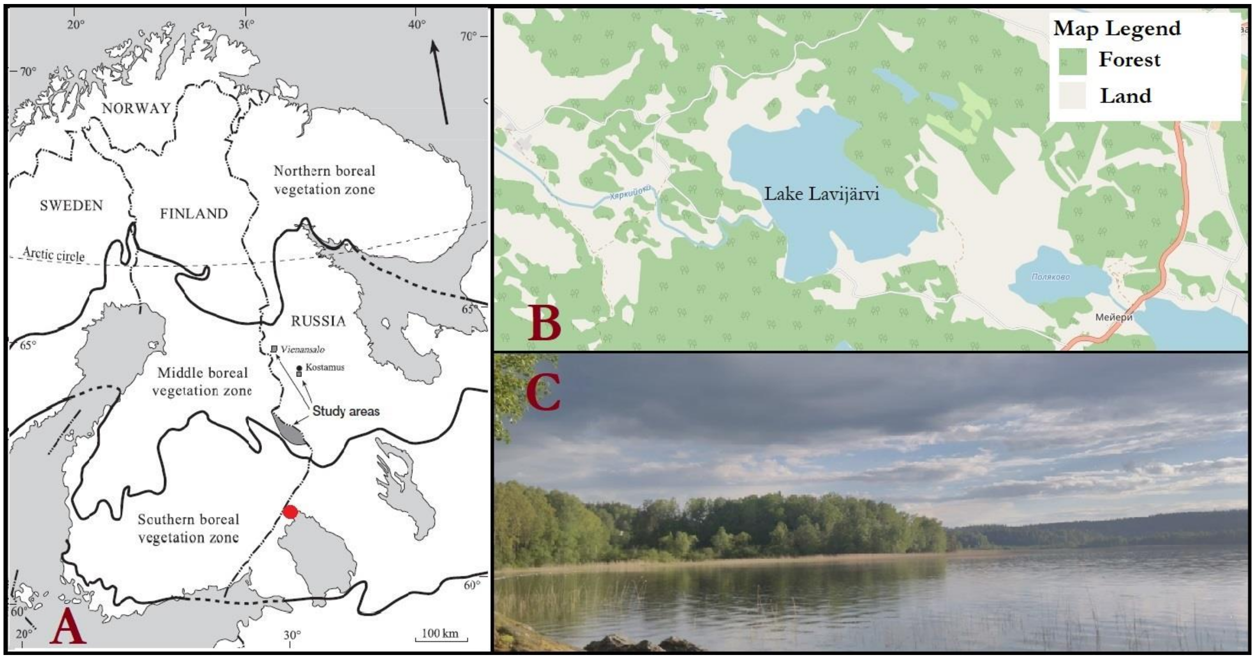

Figure 2: Map overview, A: ● location of study area in the vegetation zones map (vegetation zones after Ahti et al. 1968, map courtesy of Uotila, 2004), B: Lavijärvi on the vegetation map (Modified from © Esri ArcGIS maps 2017) and C: photo of coniferous forest surrounding the study area (picture credit: google earth)

Chapter 2: Literature Review

2.1. The general application of palynology for reconstruction of environment

Modern palynology is a rather young science since its establishment is dated to around 1916 (Manten, 1966). Hence, pollen analysis has become a tool to understand and interpret a variety of subjects. To name a few, archaeology, ecology, hydrocarbon exploration, and of course climatology, are among the fields where pollen analysis is greatly applicable.

In this chapter, a few studies and papers will be summarized to build a better background and overview on the application of palynology for reconstruction of environmental and climate conditions. The present thesis will also use fairly the same methods to identify, analyze and assess pollen grains and past climate.

In a study done by Johansson (2013), pollen and other proxies such as sediment and tephra were analyzed to reconstruct past environmental and climate change in Hjaltadalur, Skagafjördur, north Iceland. Sediments cores from Viðvik peat in the valley of Hjaltadalur, northern Iceland were drilled and inspected for pollen, loss on ignition and other proxies. From her findings, Johansson describes that in the uppermost sequence of the core, the *Compositae* pollen also known as *Asteraceae*, is the abundant taxa. Several hundred years before the abundance of *Compositae*, a decline in *Betula* pollen is seen along with an incline in the pollen curve of Gramineae also known as *Poaceae*. Johansson goes on to explain that this progress concedes with the idea of transition of a warm dry forest landscape to a cooler humid open grassland during the last 5000 years. In-addition, Johansson argues that the studied land of Viðvik was in a relatively pristine condition up until the Landnám period (1080 to 1020 BP), "when humans first started to colonize the island" (Johansson, 2013). She elaborates that even though early human settling in the area began at the Landnám period, pollen curves suggest that the increase in Gramineae pollen (a notable human presence indicator) and decrease in *Betula* started well before the start of human colonization of the island. Therefore, Human presence and activity is not the sole accountable factor for the transition of the landscape.
Johansson's study in an example of a well-used pollen analysis to investigate not only the climate change discussion, but also as a practical tool to inspect human activity and its influence on the environment. Her work shows that even though it was assumed that the change in landscape is the consequence of early human settlements, the transition in fact, occurred earlier than previously imagined (Hellqvist et al. 2016). This study is an instance of where pollen analysis can generate new findings and even improve and reform past concepts. The present thesis is also considerably similar to the work done by Johansson (2013) as it is also trying to examine vegetation types, climate changes and human impact in the selected site of Lake Lavijärvi in Karelia .

In another paper, human impact on Akita-sugi cedar (Cryptomeria japonica) forest in the late Holocene is studied to understand the detailed history of such forest in order to help sustain their utility (Kitagawa et al. 2016). Akita-sugi (Cryptomeria japonica, Japanese cedar that is grown in Akita) forest is among the forests that are financially valuable in Japan. In this paper (Kitagawa et al. 2016), pollen extracted from annually laminated lake sediment cores from Ichi-no-Megata on the Oga Peninsula, Akita, Japan is studied to find out the history of Akita-sugi cedar forests. The authors explain that *Cryptomeria* and *Fagus crenata* are the abundant and most dominant species of the area around 1000 cal BP. The pollen analysis done in the study showed that the main loss of woodland happened during the 11th century AD, when agriculture and land cultivation replaced the forests. A second loss of woodland also took place at around 16th century, when the remaining forests were cut for their timber. The Akita-sugi cedar is dated back to ca. 1700 cal BC based on the pollen analysis done. This is rather earlier than what was previously written (Hibino et al. 1979; Kawamura 1977; Tsuji 1981; Tsuji and Hibino 1975). The pollen analysis also suggests that the Little Ice Age impact on the area in the 18th century prevented any recovery of the forest albeit the Aktia government tried to restore the forest cuttings (Totman, 1985). The authors at the end try to put a high emphasis on the efforts that need to be done in order to conserve this natural forest. This case study is yet another example of the use of pollen analysis for the reconstruction of past vegetation. Though the goal of this study was to establish understanding so that the natural Akita-sugi cedar forest could be preserved, nonetheless, pollen analysis is shown as a powerful tool to be used for environment and habitat understanding and management.

2.2. A background on pollen analysis in Lake Ladoga

There have been several studies done (Alenius et al. (2004); Grönlund and Asikainen, (1992); Alenius (2007); Vuorela et al. (2000)) regarding paleoenvironmental analysis in the Karelian Lake Ladoga region. In a recent paper, Miettinen et al. (2005), studied and used pollen analysis and other limnological proxies of several lakes in the Ladoga area to investigate the growth and cessation of agricultural land use. Lake Lavijärvi is among the lakes that they studied. Lavijärvi is situated in the fertile low-lands near Ladoga with post-glacial clay covered beds (Lintunen et al. 1998). Lake Ladoga breached over the basin of Lavijärvi during 5000 to 3000 BP, reaching about 20 m (Saarnisto and Grönlund, 1996). In their study, Miettinen et al. sampled pollen at every 5 cm steps in an 86 cm long frozen core. Their analyses showed that, cereal cultivation began to appear at 65 to 55 cm depths and the herb and cereal proportion of the pollen inclined up until 40 to 30 cm depths when it reached its peak. From then onwards between the sediment level of 30 to 25 cm the spruce pollen increased which shows a cessation in agriculture and cereal cultivation.

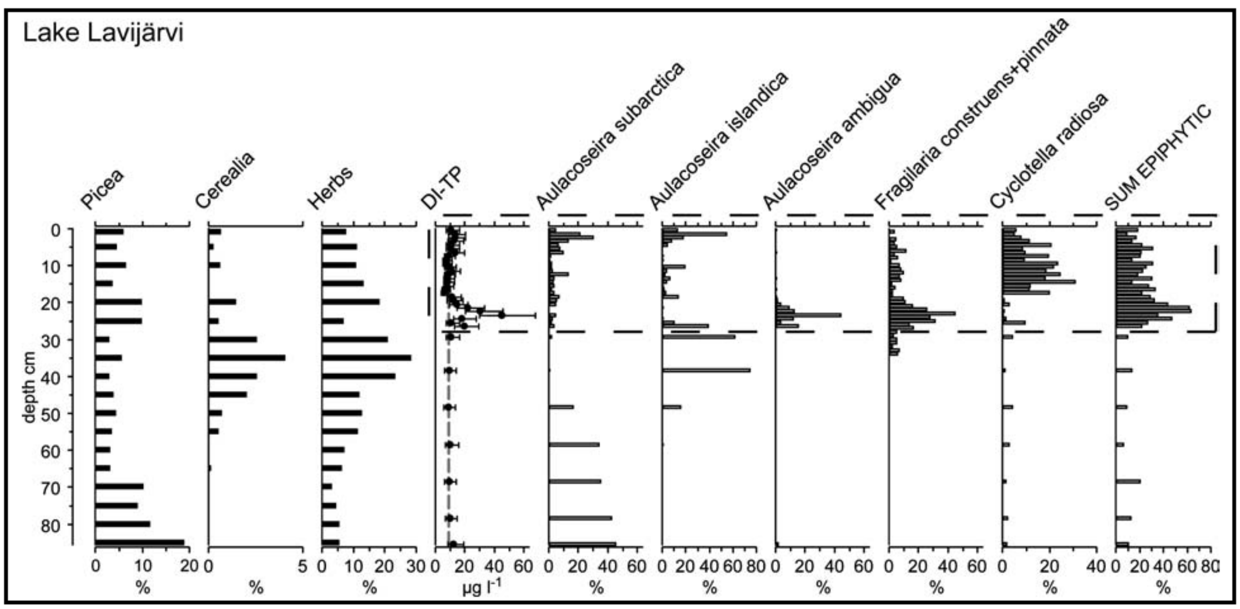

Figure 3: "Relative abundance (%) of spruce (*Picea*), cereal and herb (terrestrial non-arboreal) pollen, relative abundance (%) of some diatom taxa and epiphytic diatoms in the diatom assemblages, and diatom inferred total phosphorus (DI-TP; lg l_1) for the sediment depths 0 to 86 cm in lake Lavijärvi. Background DI-TP level in the lake is indicated by a dashed reference line in the DI to TP diagram. Analyses from freeze core sample, except diatoms 0 to 27 cm from a Kajak core (rounded with dashed line)." (Credit: Miettinen et al. 2005)

Overall, from palynological and historical records, it is implied that the agricultural and farming activities in the area began gradually but increased until 1930s and ceased around the beginning of World War II. The eutrophication, although short, intensely impacted Lake Lavijärvi in the 1930s. Though the trophic level reclaimed its status to the pre-eutrophication levels, the diatom flora of the lake had not been able to recover to its original conditions. (Miettinen et al. 2005).
This paper is among the studies done regarding the subsidiary lakes' sediments around Lake Ladoga. Lavijärvi which is this study's target lake as well, is analyzed by means of pollen and diatoms. Therefore, the mentioned paper gives a beneficial background about pollen, limnological and environmental status of Lavijärvi that will be used in this thesis.

Chapter 3: Materials and Methods

3.1. The coring

Three lakes around Lake Ladoga catchment, Lavijärvi, Pitkajarvi and Kuokkajarvi were chosen to be cored for sediments. The reason behind this selection was that these lakes are known to have had a shift from intense agriculture to pasture. Among the Russian lakes cored, Lake Lavijärvi presents the most distinctive land use shift. Considering this transition into account, pollen grains were collected and analyzed only from Lake Lavijärvi's core.
In Spring 2016, several 130 cm long sediment cores were extracted from the deepest part of the lake (25m water depth), using a gravity corer system (where a heavy weight is attached on to the liner, after that it falls through the water column into the sediment) from the frozen Lake Lavijärvi. The sediments were taken in the accumulation zone (usually the deepest part of the lake). The core was then wrapped and transported to the sedimentology lab at Eawag (Swiss Federal Institute for Aquatic Science) in Dubendorf, Switzerland.

Figure 4: Lavijärvi sediment core (LAV16-05) cut down the middle. Top part of the core is shown in the figure

3.2. Pollen sample preparation

The 130 cm long core was cut into two sections with segment A ranging from 0 to 65 cm and segment B from 65 to 130 cm. In the first steps the cylinder cores were split lengthwise down the middle. One section was used for sampling and the other half was stored in the lab's cold storage as archive. A very thin layer of the sediment surface was scraped softly with a normal knife to remove any contamination. The knife was then used to slightly cut the sediment in horizontal sections to determine the borders of sampling. Sampling for pollen was done with a cubic cm sampler. All samples were placed in plastic containers, labeled and refrigerated.

The chemical preparation of pollen samples took place in the palynology laboratory of the University of Bern. Approximately 12 hours before the chemical procedure began, 1 lycopodium tablet per sample was soaked in polypropylene test tubes with distilled water. Lycopodium tablets are used in pollen analysis to determine microfossil concentration (Stockmarr, 1971). In the next several steps, samples were washed with distilled water, treated with hydrochloric acid (HCL10%), potassium Hydroxide (KOH10%), hydrofluoric acid (HF40%), glacial acetic acid (CH_3COOH-100%), acetic acid anhydride + sulphuric acid ($(CH_3CO)_2O$+ H_2SO_4 96%). All the pollen chemical preparation protocol was done according to Moore et al. 1991. After the chemical preparation, the samples were mounted with glycerin and Fuchsin and the 22x32mm microscope slides edges were closed with wax.

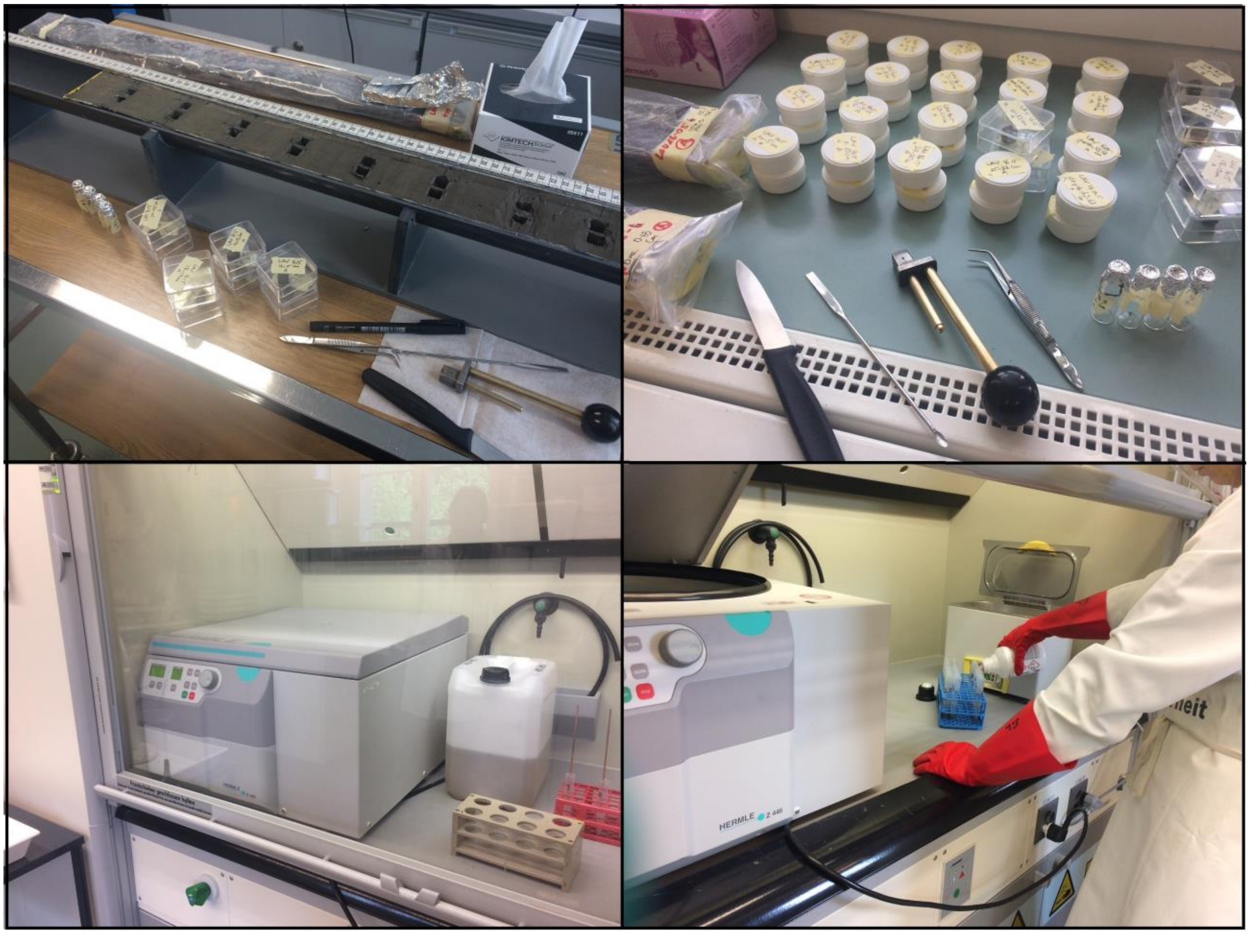

Figure 5: The pollen preparation shown in the pictures above. Sampling campaign (top photos) and chemical preparation in the lab (lower photos), (credit: author)

3.3. Pollen counting protocol

The sampling strategy was to sample 20 samples and take a sample almost every 30 years (according to the initial ^{210}Pb dates). Since the period of WWII was in great interest, 10 additional samples were taken during that period meaning every 7 years (again according to the initial ^{210}Pb dates). Thus, 30 samples were taken overall to be analyzed.

A minimum of 200 pollen were counted on each slide except for slide 1 (the surface slide) that lacked enough pollen and 156 pollen were counted. On some slides due to abundance of pollen, around 350 pollen were counted. Presence of charcoal was noted in the slides, though not specifically counted. All pollen were counted using a Leica light microscope DM series.

3.4. Pollen diagram preparation

After the pollen counting and identifying procedure using a temporary guidebook on pollen identification (Bigler et al. 2016. Advanced Plant Biology: Paleoecology [class handout]. Institute of Plant Sciences, University of Bern) the data was transferred into Excel and then to the application TILIA and TILIA.GRAPH v. 2.0.41 software (Grimm 2015), to be evaluated for the abundance of different taxa and pollen peaks through the timeline. The pollen counts were also diagramed using this application.

3.5. ^{14}C and ^{210}Pb dating

Initially, samples were dated using ^{210}Pb measurements of the natural radioactivity in the sediments (Appleby and Oldfield (1978), Appleby (2008)). It is an estimation of the sedimentation rate under the assumption of a constant supply of unsupported ^{210}Pb from the atmosphere. Due to the short half-life of lead 210, the dating only works for short temporal scales (max 100 to 150 years). From the ^{210}Pb extrapolated sedimentation rate of the upper part of the core, the samples went back to about 500 years with the oldest sample being dated around 1500 AD or 450 BP (see figure A and table 1 in appendices). Once ^{14}C dating was done, the samples dates went much further back with the oldest sample dated to around 2800 years ago. ^{14}C dating was done with a MICADAS (Mini Carbon Dating System) at the ETH Zurich. The measurements of the MICADAS system and cleaning procedure of the macrofossils was done according to Hajdas et al. (2017). Small twigs, seeds and woody remains are among the macrofossils used for ^{14}C dating. It is assumed that macrofossils represent the age of sedimentation, meaning the age of the sediment layer can be known. The macrofossils were cleaned using an Acid-Base-Acid treatment to remove all contamination. Seven macrofossil samples at 5.5, 48.5, 49.5, 60.5, 79.5, 87 and 127.5 cm depths were measured for the ^{14}C dating respectively.

3.6. Geochemical indicators and other analyses

Other than the pollen analysis used in this thesis, other geochemical indicators were measured, though these measurements will only be represented in a glimpse and will not be discussed in detail. Geochemical indicators measured include total organic carbon (TOC), total inorganic carbon (TIC), total nitrogen (TN) and total sulfur (TS). Grainsize and water content measurements were also done.

Chapter 4: Results

4.1. Dating

^{210}Pb and ^{14}C dating

In all water bodies such as oceans and lakes, the accumulation rate of sediments can be measured by use of ^{210}Pb method. In a typical measurement of ^{210}Pb in a sediment core, the average accumulation rate goes somewhere about 100 to 200 years ago. In our study, the extrapolated ^{210}Pb sediment rates went back to about 500 years ago (the assumed dates can be seen in table 1 in column "age" in the appendices). From the accumulation rate, the age of sediment from a particular depth in the sediment column can be estimated. The modelled ^{210}Pb dates only work for short timescales. The sedimentation rate derived from the ^{210}Pb dates differs in depths of 0 to 10 cm and from 10 to 137 cm.

However, the general sedimentation after calculation is 0.279 cm per year (figure A in appendices).

Age-depth models are usually produced using a limited number of sample dates. For instance, in our study 7 samples were used for ^{14}C dates. For accurate correlation and comparison of the stratigraphical proxy records with each other, constructing an age-depth model and its assessment is a fundamental requirement (Trachsel and Telford, 2017). Compared to ^{210}Pb dating, ^{14}C dates provide a more factual chronology to sediments with long temporal scales. ^{14}C dates can be applied to older sediments, since the half-life of ^{14}C is much longer (5,730 years) than ^{210}Pb. The results of the ^{14}C dates taken from seven samples of Lavijärvi are shown below as a linearly interpolated age-depth model.

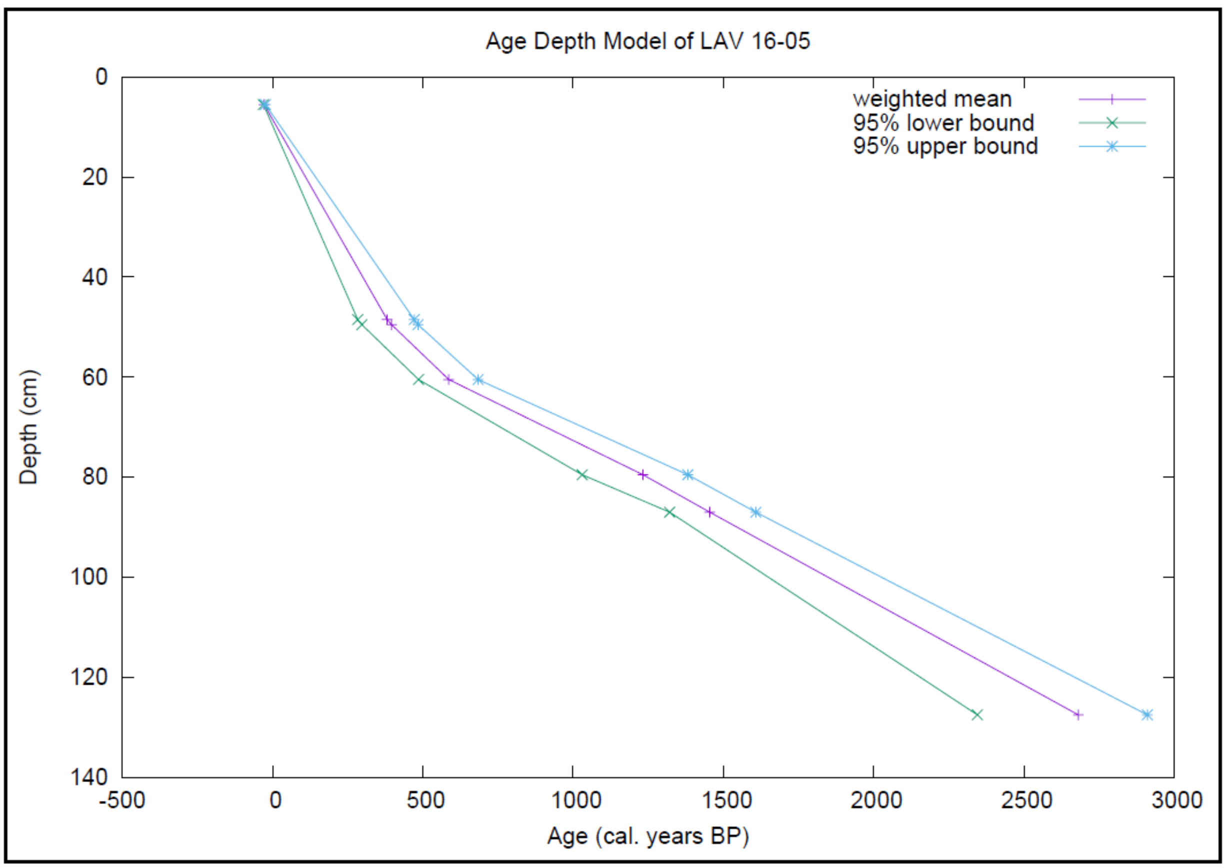

Figure 6: The linear age-depth model of core LAV16-05 based on 7 ^{14}C dates (credit: author)

The age-depth model was created using Gnuplot program from 7 AMS ^{14}C dates. The median ages of all depths along the core is shown as the violet line in a linear interpolation. The violet points on the violet line represent the calibrated AMS ^{14}C dates. The blue lower line and the green upper line show 2 sigma 95% confidence intervals of the modelled age depth relationship. As shown in the figure 6, the sediment chronology of Lavijärvi goes back to about 3000 years ago. This timeframe is interesting since the pollen record can show us the late Holocene changes in vegetation and climate. The dating of core LAV16-05 revealed that the core goes back to 2700 cal BP (median). The sedimentation rate shows some variations through the core, though it seems to have almost stayed the same from the beginning of the core until about 450 cal BP. After that, the sedimentation rate decreases until about 550 cal BP. After 550 cal BP, the sedimentation rate decreases furthermore and stabilizes for about 700 years and then increases slightly towards the oldest part of the core.

4.2. Pollen data

The result of the pollen counts and percentages of core LAV16-05 is represented on the next pages. In the time frame of ca. 2800 cal BP to now, a total of 21 pollen and spore types were identified from the sediment core. Among these 21 pollen and spore types, 19 pollen taxa were identified and 17 of them are shown in the diagram on the next page. The 2 omitted taxa from the figure are *Corylus* tree pollen and the herb, *Urtica*, since their abundance were insignificant and negligible (about 1 pollen of each taxa in the whole core). The dominant vegetation type was the arboreal trees and shrubs throughout the whole core. *Pinus* was the most dominant species with average of 33.7% followed by *Betula* with average of 24.02%. The third dominant species was the herb community of *Chenopodiaceae* with an average of 14.7%. Aquatic taxon of *Isoetes* represented an average of 4.8%, which is even more significant in some intervals. Colorful curves represent the raw data of pollen percentage while due to the limited count of some pollen taxa, all pollen histograms are exaggerated by a factor of x20. The hollow curves represent the exaggerations. Figure 8 also displays the pollen percent diagram with a more simplified terminology of pollen taxa. In this diagram again, some taxa have been skipped because of their low abundance. Among the counted pollen there are unspecified pollen species either because they had been decomposed, broken or at a difficult orientation to be identified. Though, despite of this fact, almost all of the pollen existing in each sample were identified and counted.

The Plants and trees of boreal forests such as around Lake Lavijärvi are adapted to harsh climate conditions like long, frigid winters, short, dry summers, and frequent fires. Therefore, boreal forests are mostly dominated by coniferous species since they can undergo adverse environmental conditions and survive (Larsen, 2013).

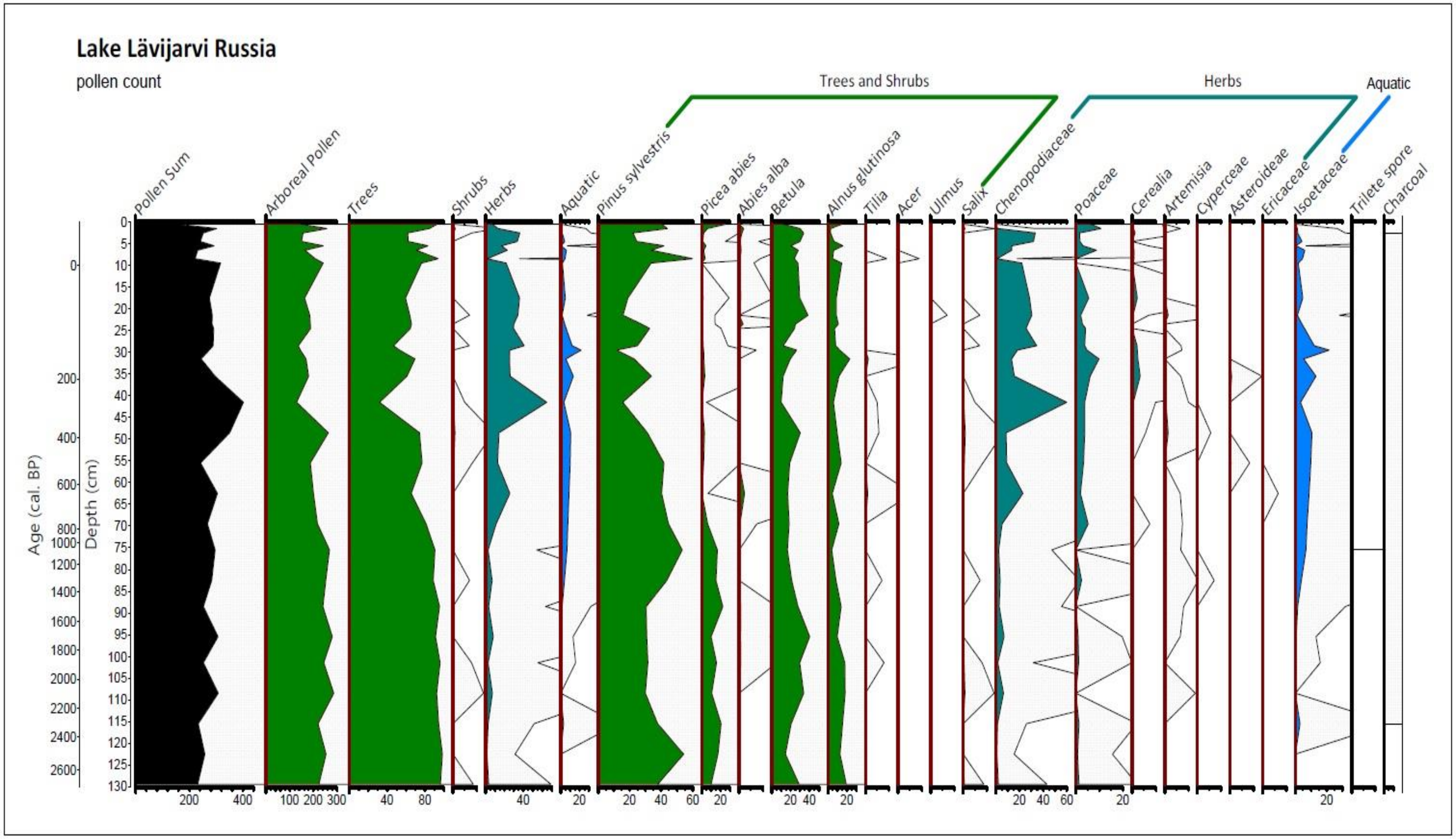

Figure 7: The pollen percentage diagram of the Lake Lavijärvi's core (LAV16-05). The pollen sum and arboreal pollen histograms are represented as raw counts and not percent. (The age bar used correlates with the Bayesian age depth model in the appendices).

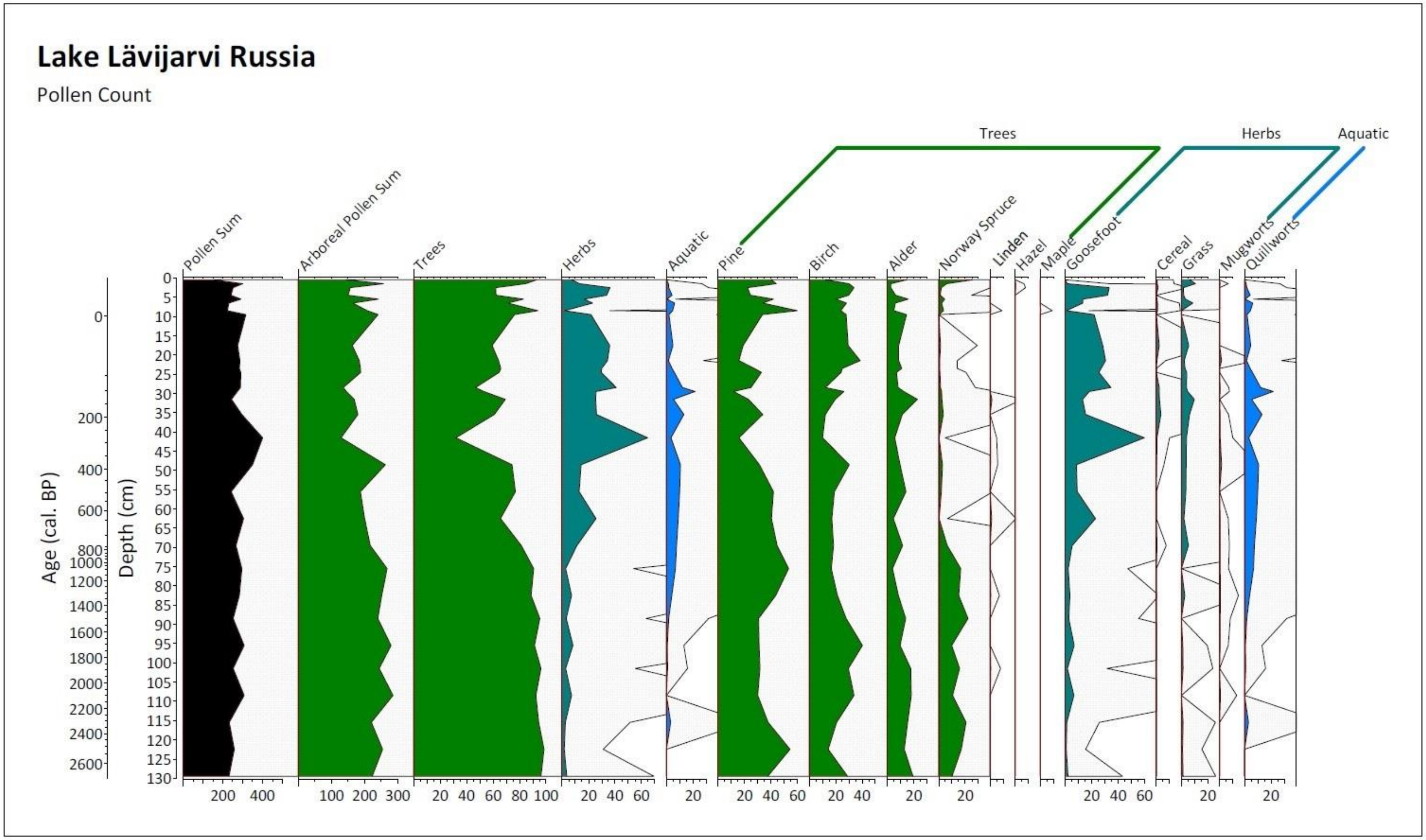

Figure 8: Pollen diagram of Lake Lavijärvi with more simplified pollen taxa terminology. The simplified terminologies are corresponding to the previous figure as below: Pine= *Pinus sylvestris*, Birch= *Betula*, Alder= *Alnus*, Norway Spruce= *Picea abies*, Linden= *Tilia*, Hazel= *Corylus*, Maple= *Acer*, Goosefoot= *Chenopodiaceae*, Cereal= *Cerealia*, Grass= *Poaceae*, Mugworts= *Artemisia* and Quillworts= *Isoetaceae*

Figures 9 and 10 present photos of some of the pollen taxa taken while counting with the camera attached to the light microscope used for pollen identification.

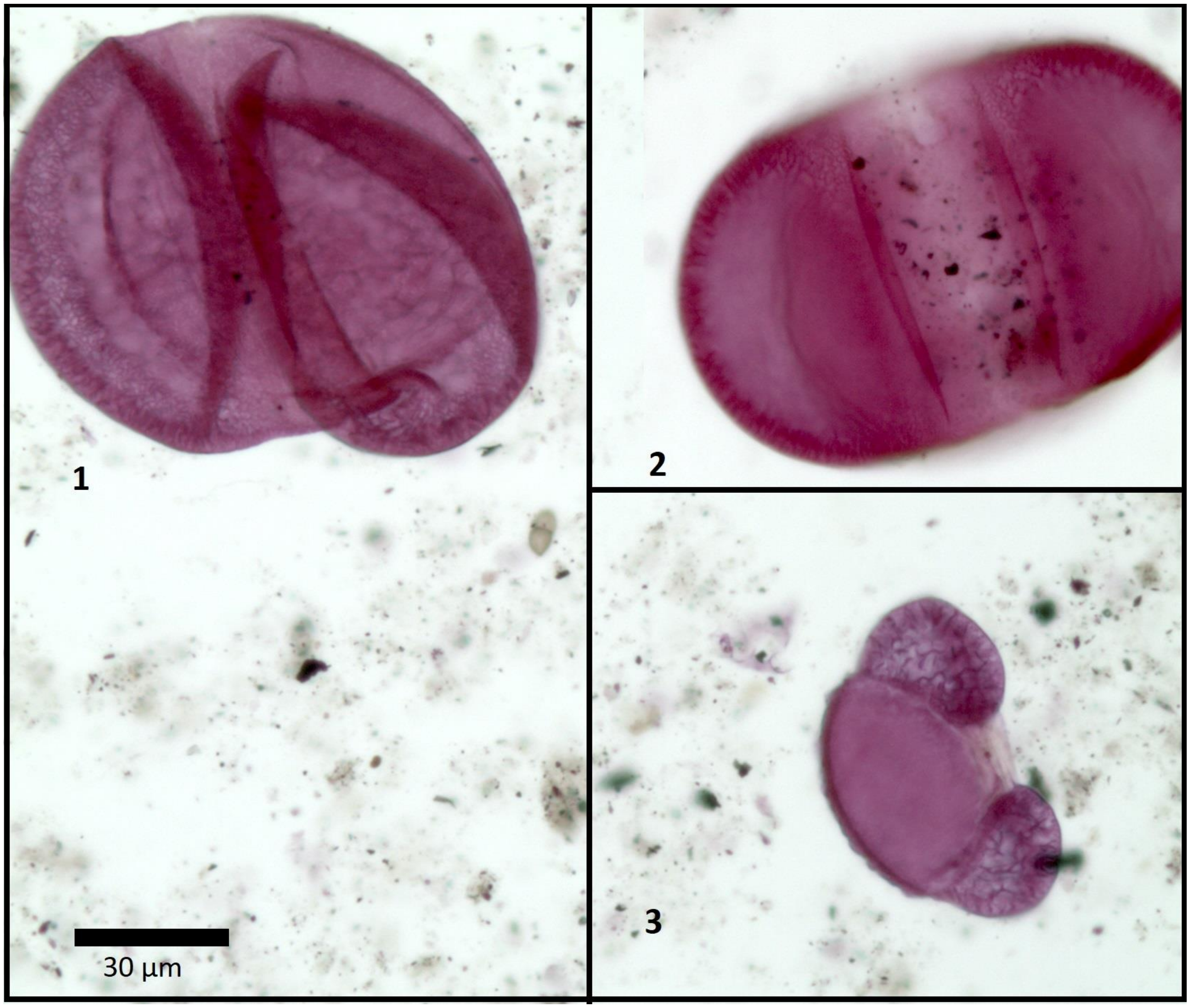

Figure 9: Pollen grains of *Abies alba* (1), *Picea Abies* (2) and *Pinus sylvestris* (3). The scale bar serves for all 3 taxa shown. Note the foldedness of the *Abies alba* pollen (credit: author)

The arboreal pollen of the family Pinaceae (*Abies*, *Picea* and *Pinus*) are the most dominant pollen throughout the Lavijärvi sediment core. These species are among the wind-pollinated grains that can travel long distances. Due to their thick regulate exines (outer walls), these evergreen conifers are resilient to harsh weather condition and other environmental risk factors that can destroy them. Thus, making them a strong proxy to record coniferous vegetation changes or abundance in sediment records.

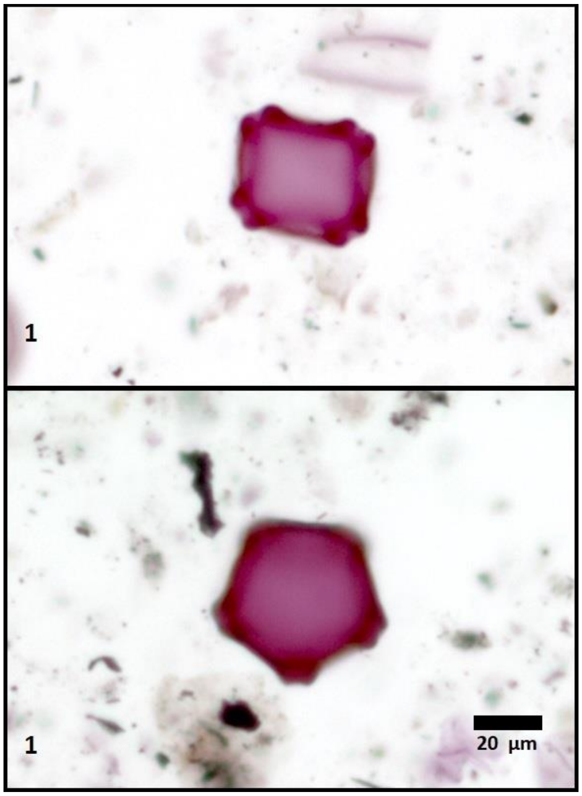

Figure 10: The pollen grain of *Alnus* (Alder) tree (1). The third abundant arboreal pollen with 10.8% abundance in the whole core (credit: author)

Alnus pollen can be either found with four or five pores. Though, the abundant type in the Lavijärvi samples were the 5 pores type. They consist of thin scabrate exines with thick bows that connect each aperture to its neighbors. *Alnus* is also among the wind-pollinated species that is transported to great distances from the nearest possible source as well (Dowding, 1987).

4.3. Geochemical analyses

As mentioned previously in the text, other proxies such as total organic carbon, total nitrogen, C/N and total sulfur were also analyzed at the Eawag and ETH institutes in Zurich.

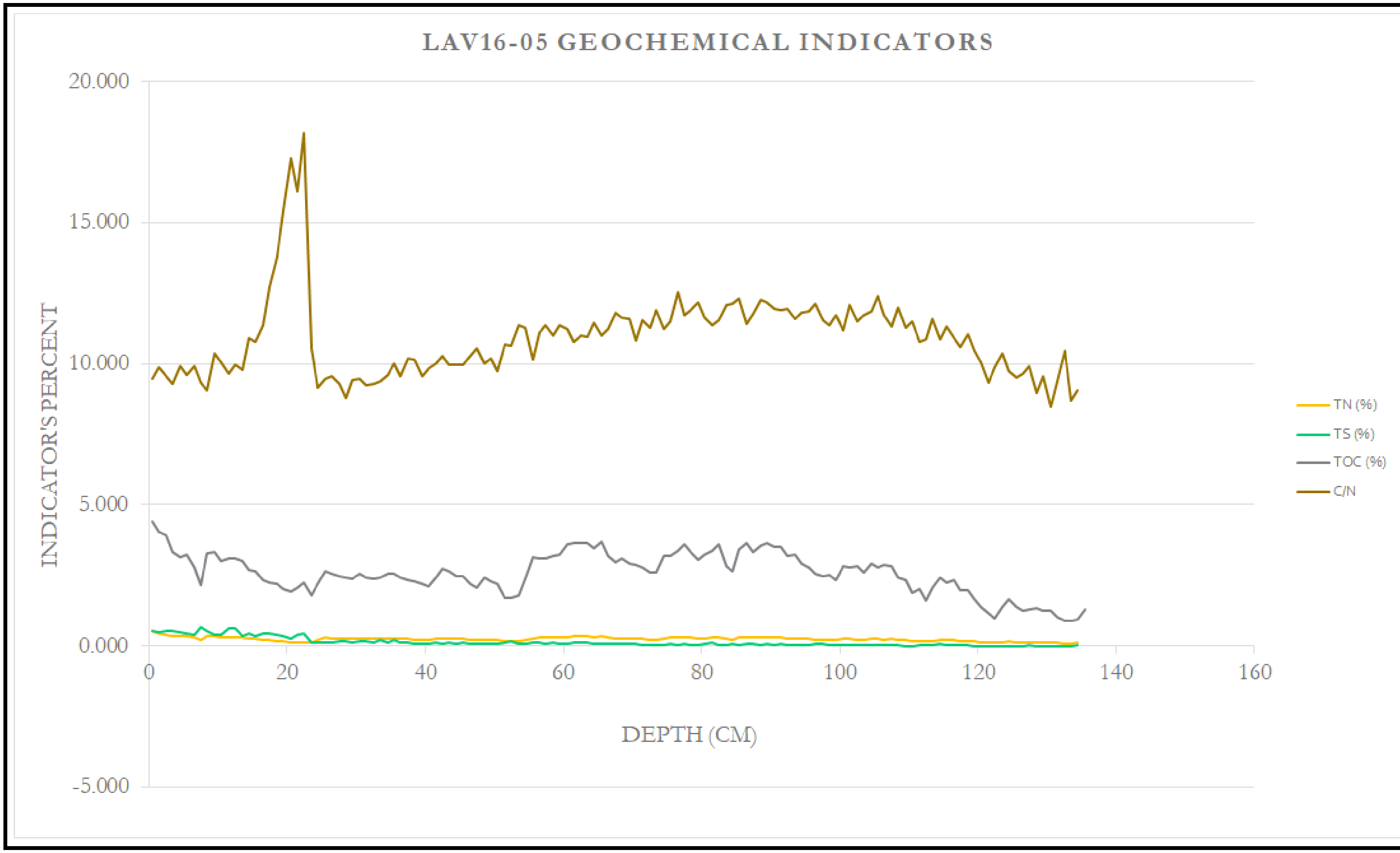

Figure 11: The geochemical indicators of Lake Lavijärvi as percentages against the core depth. The graph represents TN% (Total Nitrogen), TS% (Total Sulfur), TOC% (Total Organic Carbon) and C/N (TOC/TN)

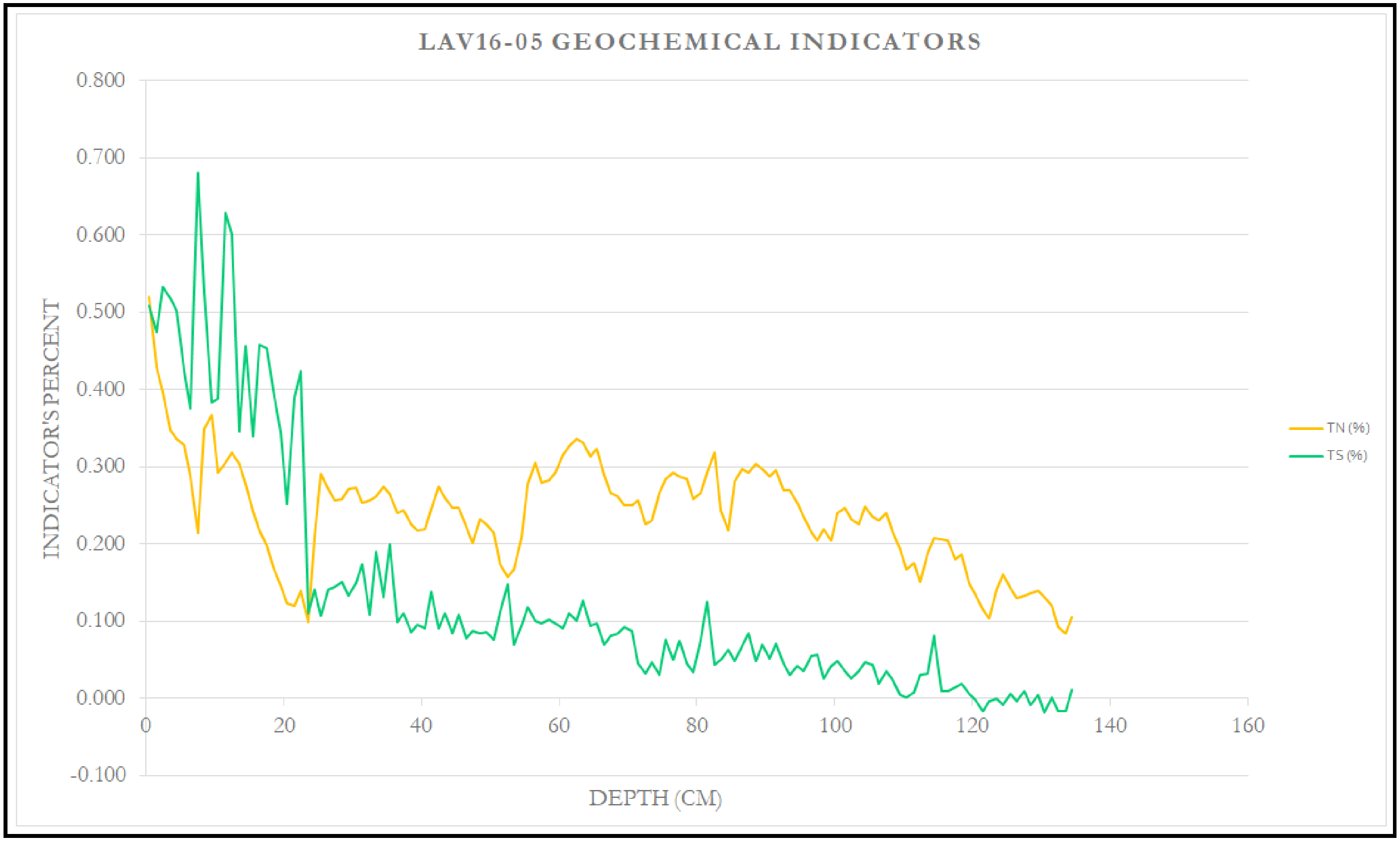

Figure 12: The geochemical indicators of Lake Lavijärvi as percentages against the core depth. The graph represents TN% (Total Nitrogen) and TS% (Total Sulfur)

Chapter 5: Discussion

5.1. Pollen analyses

From the Lake Lavijärvi pollen analyses results, 4 main periods of environmental changes were determined: 2700 to 1400 (Zone A), 1400 to 650 (Zone B), 650 to 10 (Zone C) cal BP and 10 to -66 BP (Zone D).

Zone A (2700 to 1400 cal BP): Zone of consistent forest

Zone A (~2700 to 1400 cal BP or 750 BC to 550 AD) is initially dominated by *Pinus* (~40%) and *Betula* (~20%) followed with *Alnus* (20%). Herbs species are rather low and infrequent at this stage, though presence of *Salix*, *Chenopodiaceae* and *Poaceae* can be identified. This initial pollen amount and lack of considerable herb or non-arboreal pollen supports the idea of a dense, thick coniferous-deciduous forest with almost no openings. Since *Pinus* and *Betula* are both light-demanding and rather pioneering trees that often spread after disturbances such as fire and clearings, it can also be inferred by the dominance of these species in this period that the forest has survived some type of disturbance and, consequently, the growth of *Pinus* and *Betula* as the main vegetation has created a landscape of a dense mixed forest (Li et al. 2008).

According to Huusko and Hicks (2009), *Pinus* and *Picea* pollen can be considered as proxies for the summer temperatures centered around July. The reason behind this argument is that these species' pollen production is quite high in comparison to other coniferous pollen and the fluctuations between year to year pollen production (considering a consistency in the pollen production over the observed time) can determine a flowering temperature limit for *Pinus* and *Picea*. This temperature limit has been suggested at average 12°C and 13°C for *Pinus* and *Picea*, respectively. Thus, it can be assumed that the mean July temperature of Lake Lavijärvi in the time window of Zone A is varying between favorable temperature for these taxa since the abundance of vegetation is dominated by *Pinus* and steady presence of *Picea* throughout this period. The peak of *Pinus* at around 2400 cal BP hints to a very favorable temperature and other environmental conditions for Scots pine (*Pinus*) growth. As mentioned, both *Pinus* and *Betula* are light-demanding trees (Li et al. 2008) and, when coexisting, they are looking for mainly the same resources in their habitat. This will result in a competition between the species and usually the species that is stronger and more tolerable towards unfavorable environmental conditions succeeds and grows wider. This can also be the case between *Pinus* and *Betula*. Though both trees need light, *Betula* cannot survive in sunlight deficiency, whereas, *Pinus* has the characteristic of continuing to grow in shortage of light (Vedel and Lange, 1960). In the Lavijärvi record, around 2400 cal BP there is a peak of *Pinus* that coincides with a slight decrease in *Betula* and *Alnus* pollen. This can be explained by the mentioned species competition theory. Moreover, *Betula* is known to do best on dry acidic soils, whereas, tough *Pinus* also prefers acidic soils, it can also grow in alkaline dry-moist soils and can tolerate drought ("Plants for a future", www2). *Pinus* and *Betula* are both humid sensitive plans. Though known to be tolerative of dry soils, both species bloom best in the average annual precipitation of ~800 mm (Sun et al. 1996).

Zone A is characterized by presence of *Chenopodiaceae* and brief presence of *Artemisia* around 2300 cal BP. Though low in distribution, these species grow in somewhat dry and cold climate (Andreev et al. 2016). Thus, considering their small population, it can be inferred that the climate was probably not their optimum during this period and it was moister than these species preferred. *Chenopodiaceae* is a perennial herb that prefers drier climate (favorable annual rainfall around 100 to 800 mm). On the other hand, *Artemisia* and *Asteraceae* (though perennial herbs as well) prefer wetter climate (favorable annual rainfall around 300 to 1000 mm). Therefore, the relative dominance ratio between these plants indicate whether the climate was more to the wet or dry side (Mensing, 2001). Throughout Zone A, *Chenopodiaceae* seems to be the dominant herb. This is also the case

for the whole core as well. This indicates that throughout this 3000 years' time-window in this region, the climate was rather dry than wet with some exceptions according to the A/C ratio (*Artemisia/Chenopodiaceae*) described by Mensing, 2001. This is a relative ratio since moisture seems to be available throughout the core as well.
As mentioned before, *Pinus* can tolerate drought and the peak of it around 2500 cal BP, can now also be supported by the presence of *Chenopodiaceae* and its small increase in that time, as *Chenopodiaceae* can also endure dryness.

Along other species that are briefly present during Zone A are *Isoetes* or Quillworts. *Isoetes* are aquatic and semi-aquatic species that grow mostly on shallow ponds and lakes. The plant thrives best on stagnant bodies of water (Stace, 2010). *Isoetes* growth is limited to lakes and wet grounds, thus, it can be assumed by the presence of this species during this time and along the whole core that Lavijärvi is a perennial lake that has existed for the past 3000 years. The proliferation in *Isoetes* population can also indicate lower lake levels and probably reduced precipitation (Behling and Hooghiemstra, 1999). Quillworts flourish in light intensive lakes that have rather high productivity (Miettinen et al. 2002).

In addition, *Picea* (Spruce) pollen is also well-represented in Zone A. *Picea* pollen is known to be heavy and large in size and therefore about 50% of the pollen usually travels to a 500-meter radius of the source at the wind speed of 4 m/s and 25% of pollen travels to a 2km radius and deposits (Schmidt-Vogt, 1986). It can be assumed that the considerable (~20%) population of *Picea* that is present in the pollen count came from the vicinity of the lake. Therefore, *Picea* forest was notable in the lake's surroundings and vegetation cover. *Picea* is also known to be a good indicator of fire episodes in forests as the tree is very vulnerable towards fires and is easily killed in ignited areas as opposed to *Pinus* that survives fires (Pitkänen and Huttunen, 1999). The continuous steady presence of *Picea* in Zone A would indicate that the forest surrounding the lake was fire-free or at least fire episodes were limited at that time.

The pollen indicators of human activity and cultivation such as *Poaceae* and *Chenopodiaceae* is very briefly represented in the pollen counts, and therefore, their presence and its interpretation will be discussed thoroughly in the next phases, when they are much more abundant.

Overall, Zone A is best described by an arboreal forest landscape (above 80% in trees population) with minimum presence of herb taxa. Conifer trees such as *Pinus* and *Picea* are abundant with about 40 to 50% of the population. The rest of the forest is dominated by deciduous trees like *Betula* and *Alnus* with about 20 to 40%, while Herb species such as *Chenopodiaceae* are rarely present (less than 5%). The aquatic herb of *Isoetes* is also briefly presented (about 3%) during this period. The climate is assumed to be more humid than today with more average precipitation (see figure 13) as humid sensitive taxa such as *Pinus*, *Betula*, *Picea* are present to a good extent (Sun et al. 1996) though still to the drier side according to the A/C index mentioned by Mensing 2001. There is no noticeable fire record according to the steady *Picea* population in the record, or any considerable human-land-use-indicative plants for this period. Though limited pollen of *Poaceae* are recorded at 130 cm, 115 cm and 95 cm. This can be a result of either a certainly minimal cultivation of barley or reworking of sediments and sediment contamination. Either way, the sporadic and small presence of *Poaceae* is negligible in this Zone.

Zone B (1400 to 650 cal BP): Zone of transition from forest to forest-steppe

Following the end of Zone A at ~1400 cal BP, Zone B extends from ~1400 to ~650 cal BP or 550 to 1300 AD. Zone B is a rather short period compared to other zones, that can be recognized as a zone of transition. In general, Zone B exhibits the last remaining population of

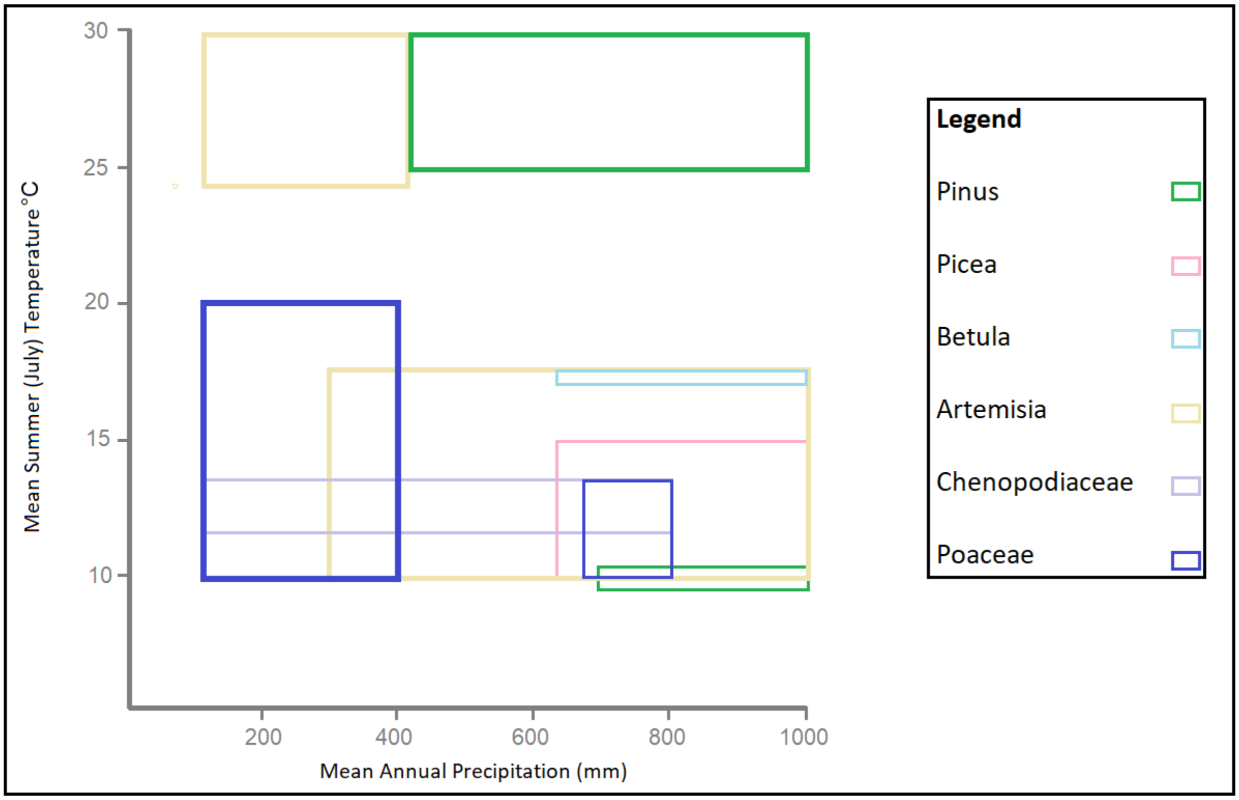

Figure 13: A synthetic mutual climatic range diagram showing frequent pollen species approximate climate range. The diagram is generated using the synthetic climatic range model from Brewer et al. (2007) and concepts from the paper by Sun et al. (1996) (credit: author)

Picea before its lengthy cessation, demonstrating a gradual shift of the landscape from a dominantly coniferous forest to more openings and the first distinct emergence of *Poaceae*. The Pine population experiences a high peak during Zone B. This sudden increase of *Pinus* pollen coincides with a gradual decline in *Picea* pollen and a steady *Betula* population. The abrupt increase of *Pinus* can perhaps be explained by the first substantial cultivation of *Poaceae* by a slash and burn episode. An episode of slash and burn is when farmers slash the vegetation in an area and burn the grounds to prepare lands for crop fields and pasture. Clearings created by fire have several advantages, such as attracting game animals and improving the growth of some edible plants (Alenuis et al. 2012). The slash and burn cultivation results in a sharp and noticeable decrease in *Picea* population since the plant is excessively vulnerable to burnings and can't survive habitat fires. The stable *Betula* pollen also compensates for the decrease in *Picea* pollen along with the emerging *Poaceae* pollen which points to lake regression (Grönlund et al. 1992) (Quillwort population agrees with this), and a gradual shift from the coniferous forest to forest-steppe vegetation. The *Pinus* as explained before, is a fire-resistant tree that also acts as a pioneer succeeding tree that grows after forest fires. *Pinus* can tolerate forest fires and can exceptionally grow during fire episodes. Thus, the sudden peak of *Pinus* and its steady population can be explained by its resistant nature.

After the sudden peak of the *Pinus*, the tree population along with *Picea* begins to take a decreasing trend. Heikkilä and Seppä (2003) explain that Spruce is an especially cold-temperature-loving plant that needs an average winter temperature of < -6.0ºC for reproduction and excessive snow to cover its seeds in winter (Dahl, 1998). At the beginning of Zone B, there is a steady population of *Picea* that suggests cold winters for Zone B commencement, suggesting weak effects of the Medieval Warming Period (MWP). After that a rise is winter temperatures and general warming is assumed, due to both *Picea* species fall and increase in *Alnus* population which is a warm-demanding taxon that grows best in warm temperatures (Heikkilä and Seppä, 2003), implying more evident MWP responses. Moreover, since almost all slash and burn episodes are manifested via a decrease in *Picea*, it can also be inferred that other than the warming temperatures, newly cultivated *Poaceae* lands also justify the *Picea* decline.

The *Poaceae* taxon was rarely seen in Zone A. At about cal 1400 BP, at the beginning of Zone B, however, *Poaceae* seems to make a clear appearance. This perhaps illustrates the first intended and extensive cultivation of this plant by humans and possibly the first major human land-use in the surroundings of Lake Lavijärvi. *Poaceae* is a common species indicator of steppe and forest-steppe vegetation, whereas *Chenopodiaceae* and *Artemisia* dominate arid desert-steppe zones (Li et al. 2010). As seen in the pollen diagram, since all *Chenopodiaceae*, *Artemisia* and *Poaceae* pollen are present simultaneously in the area, a semi steppe-forest vegetation is considered for the surroundings of Lavijärvi. *Poaceae* is a shallow-rooted plant that needs more soil moisture than *Artemisia* while *Cyperceae* moisture demand is higher than both former plants. The presence of *Poaceae* at 1300 cal BP happens concurrently with the presence of a single *Cyperceae* pollen. Perhaps, high soil moisture levels in this period is the cause of this, and therefore, we can assume wet semi-warm climate conditions at the beginning of Zone B followed by warmer and less humid conditions. The *Poaceae* population increase furthermore in the following centuries. At 1000 cal BP, *Poaceae* experiences its first highest peak in the diagram, in the meantime a single *Cerealia* type pollen is seen. The presence of *Cerealia* pollen further approves the slash and burn cultivation episodes at 1000 cal BP. The continuous growth of *Poaceae* from this period forward also shows that the Medieval Warm Period seemingly didn't affect this area that much as the plant needs considerable moisture for growth (Mensing, 2001). Though it might have periodically and limitedly impacted the environments as discussed in the next paragraphs. *Cerealia* pollen is undeniably among major indicators of past agriculture and the presence of it at around 1000 cal BP correlates well with the presence of other *Cerealia* pollen at nearby distances such as Lake Laihalampi in eastern Finland which also experienced a rise in *Cerealia* at 1000 cal BP (Heikkilä and Seppä, 2003). This period marks the first established human land-use and notable continuous crop cultivation. Alenius et al. (2004) also illustrate that the first *Cerealia* or the absolute *Cerealia* limit (C^{o}) appeared at 1350 BP in the Karelian Island of Riekkalansaari at the north of Lake Ladoga. This indicates that the *Cerealia* limit in Lake Lavijärvi's surroundings is more recent (at 1000 BP compared to 1350 BP in Riekkalansaari) and, thus, intentional land cultivation around Lavijärvi probably took place later than in its neighboring areas. Intensive human land-use and farming also affects the ecosystems of lakes and water quality. Fires caused by slash and burn episodes and openings of tree canopy, for instance, reflected by the increasing proportion of *Poaceae*, impact the lake catchment and causes more permanent lake eutrophication. This is shown also by the increasing Quillworts in the diagram which bloom in increased pH and trophic status (Miettinen et al. 2002).

The community of *Isoetes* begin to take on an ascending trend, this, as discussed can also be the outcome of the lake's eutrophication (Farmer and Spence, 1986). *Isoetes* are known to bloom in nutrient-rich lakes (Miettinen et al., 2002). The warming at about 1000 to 900 cal BP also promoted organism growth and production of organic materials in lakes (Saarinen et al. 2001); Quillworts are stress tolerant plants that flourish in nutrient-abundant lakes. Thus, the warming at 1000 cal BP along with field cultivations resulted in lake eutrophication as displayed by the rise in *Isoetes* population. The warming, though short and not intense, can be identified as a sign of the Medieval Warming Period in Karelia. Haltia-Hovi et al. (2007), suggest high solar forcing activities according to annual varves extracted from north Ladoga. This, along with gradual mild winter temperatures and ice cover can be categorized as signs of Medieval Warming Period in north Karelia.

Overall, Zone B as discussed, is a zone of gradual transition from dense coniferous-deciduous forest to forest-steppe like vegetation. The first major cultivation indicators happen in this period along with noticeable lake eutrophication. Cold winter temperature is assumed for the beginning of Zone B with slight warming taking place near the end of the zone, suggesting signs of Medieval Warming Period that might have insignificantly impacted the area since the soil moisture remains constantly high for the growth of *Poaceae* pollen.

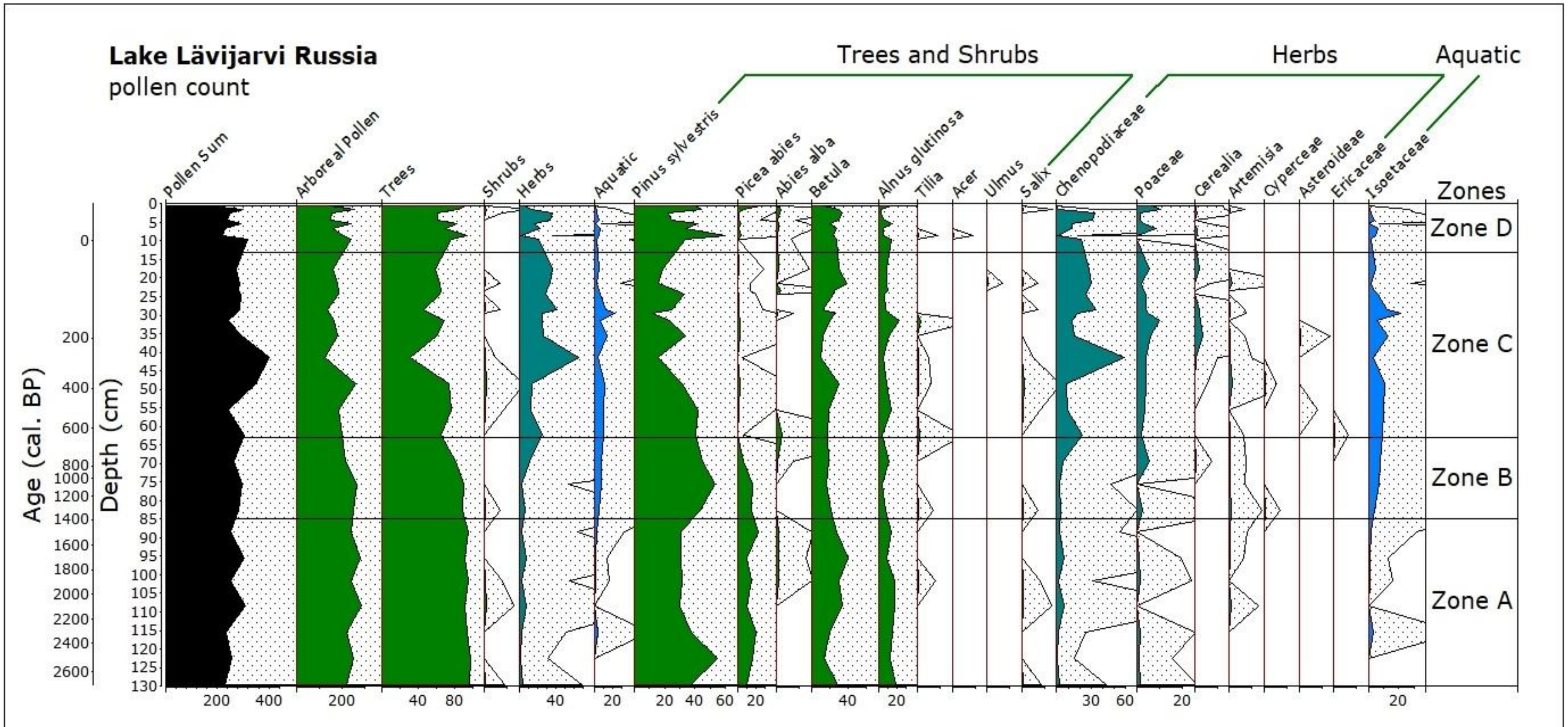

Figure 14: Pollen Diagram of core LAV16-05

Zone C (650 to 10 cal BP): Zone of fluctuations in the vegetation cover

Zone C begins around 650 cal BP and continues to 10 cal BP or 1300-1940 AD. Zone C can be described as a zone of major fluctuations throughout almost all species and an intense slash and burn cultivation. The slash and burn cultivation is carried out by rotation cycles, meaning that a presumed land is burned and cleared by fire for cultivation. After the cultivation, the lands are used usually for pasture activities. At the early slash and burn cultivation periods, the mentioned rotation cycles persist for a long time providing the natural forest of the environment an opportunity to reach maturity. However, with the progressive increasing population and intense farming, these rotation cycles became shorter and hence the time for recovering of natural forest became more limited (Alenius et al. 2004).

Zone C begins with a stable *Pinus* population for about 100 years. *Pinus* then commences a sharp descending trend that decreases the proportion of coniferous forest down to 20%. This marks the first shift of vegetation and landscape view from arboreal forest to steppe like open heathlands after about 2000 years. The *Picea* community is almost wiped out with single or very low number of pollen appearing from time to time during this period. The much noticeable decrease in *Picea* pollen along with rise of herb taxa such as *Chenopodiaceae*, *Artemisia* and *Asteraceae*, points to obvious human land-use and impact in the lake surroundings (Koff and Punning, 2008). During this time frame, *Betula* continues its steady community while experiencing a small peak at ~430, ~160 cal BP and -46 BP (1996 AD), (all coinciding with a decrease in *Pinus* pollen), which indicates good lighting conditions (Vuorela, 1995). The succession of *Betula* compensates the decrease of *Pinus* and is well consistent with the minimum *Picea* pollen. The advancement of *Betula* (among pioneering species) along with the decreasing *Picea* pollen, also yields to the fact that the environment is trying to regenerate its natural forest state, but it keeps getting interrupted by human land-use and cultivation, hence, the small peaks in *Betula*. This interruption is also well visible in the continuous yet inconsistent rise and fall of *Pinus* population

(Vuorela 1995). The Birch (*Betula*) tree is a shade intolerant pioneer taxon that grows immediately in open landscapes after fires and clearings (Hynynen et al. 2009). The tree is well grown due to its fast spreading and prolific wind pollination (Palmé et al. 2003). Therefore, the constant presence of Betula suggests that the forest and lake surroundings received enough sunlight that boosted Betula growth. Though they do not grow as immediately as Birch, Pine (*Pinus*) trees are also among other pioneer species (Stoll et al. 1994, Kunstler et al. 2004). This can be seen in the pollen diagram: the *Betula* pollen curve fluctuates less than that of *Pinus* which demonstrates two factors: First, *Betula* as discussed, often grows faster in a pioneer forest after fires and is not tolerant of shade, thus, in case of a slash and burn cultivation and openings they rapidly occupy the non-cultivated lands but need to receive enough sunlight in order to maintain their progress. Second, *Pinus* is a stress tolerant pioneer tree (Kunstler et al. 2004), that can grow even in minimal sunlight conditions, although unlike *Betula*, they take a longer time to evolve. These factors well agree to the diagram (a highly fluctuating *Pinus* pollen curve and a somewhat steady *Betula* pollen curve) and indicate that the environment around Lavijärvi from 430 cal BP onward, receiving enough sunlight, was going under stress frequently due to human land-use and cultivation. *Betula* tried to reproduce as *Pinus* tried to do the same though with a delay due to its natural stress-tolerance characteristic. Along other successional species are Alders (*Alnus*) that grow in burned areas after fires (Pitkänen and Huttunen, 1999). *Alnus* prefers nutrient-rich soils that contain high moisture and therefore are common in lakeshores (Alenius et al. 2013), moreover, Alders are known to flourish in warm temperatures (Heikkilä and Seppä, 2003). Thus, the small peak in *Alnus* usually indicates favorable climate for this taxon, e.g., warm semi-wet conditions. Except for a peak at ~150 cal BP, *Alnus* experiences a steady low (10% or lower) population throughout the rest of the core. The synchronous decline of *Betula* and *Alnus* from ~400 cal BP until ~190 cal BP and from ~160 cal BP until ~100 cal BP might indicate utilization of deciduous forest for cultivation (Alenius et al. 2004). Overall, the prominent variations in *Pinus* and *Betula* along with the distinct decline of *Picea* and presence of *Poaceae* and *Cerealia* pollen imply human activity (Vuorela et al. 2000).

The herb taxa such as *Chenopodiaceae*, *Artemisia*, *Asteraceae* (*Asteroideae*) and cultivated herb taxa, namely, *Poaceae* and *Cerealia* increase in this Zone. *Chenopodiaceae* and *Artemisia* along with *Asteraceae*, as discussed in the previous paragraphs, are moisture indicative plants. During dry and warm periods *Chenopodiaceae* and *Artemisia* increase, and their abundance suggests a mean temperature and precipitation similar to that of today's climate (Mensing, 2001). Permanent field cultivations are also associated with weed type plants such as *Chenopodiaceae* and *Artemisia* (Alenius et al. 2004). Moreover, *Chenopodiaceae* is known to be a common plant that grows in disturbed soils (Andreev et al. 2002) such as bare mineral soils in open vegetation settings (Vuorela, 1995) near lakeshore meadows (Koff and Punning, 2008). Thus, the cultivation phase, which most probably disturbed the ecosystem in the area, also impacted and promoted *Chenopodiaceae* growth. Furthermore, Heinsalu and Veski (2010) and Li et al. (2010) also point out that *Chenopodiaceae* (Goosefoot) and *Artemisia* family are clear indicators of human activity and their high frequencies in semi-arid environments along with presence of *Cerealia* and *Poaceae*, are definite signs of human land-use and settlement (Vuorela et al. 2000). In this account, the consistent high (mean: >20%) *Chenopodiaceae* population (experiencing high peaks at ~700 cal BP (20%), ~300 cal BP (60%) and ~160 cal BP (40%)) concurs with the evident field cultivation indicators and accounts for a protracted open steppe-forest like vegetation with cool and relatively dry climate (though still providing enough moisture for moisture demanding plants such as *Poaceae*). The striking notable rise of *Chenopodiaceae* at 300 cal BP marks a major vegetation shift with herb community dominating the landscape along with the lowest tree taxa rate (<40%). The high *Chenopodiaceae* population together with the highest *Cerealia* limits is also reported by Alenius et al. (2004), to have taken place in north and northwestern Lake Ladoga regions around 250 to 150 BP. This date corresponds well to Lake Lavijärvi's pollen diagram. Furthermore, Alenius et al. (2004)

state that the settings of Eastern Finland and Ladoga regions were open fields that lacked mature coniferous forest with slash and burn cultivation amounting to about 75% in north and northwestern Ladoga. This is well apparent in the rise of *Poaceae* and *Cerealia* pollen during this period. Beginning from 650 cal BP, the *Poaceae* community adopt an ascending trend reaching a peak at ~190 cal BP. This trend along with the highest *Cerealia* (rye) values suggest intense land cultivation and farming taking place in Lavijärvi surroundings. The increase in the *Poaceae* pollen represents an open steppe-like vegetation with adequate moisture present in soil (Mensing, 2001, Andreev et al. 2002). The *Poaceae* frequency also points at pasture fields for grazing (Grönlund et al. 1992). Landscape openings and Cereal cultivation supply enough proof of a developing population and increase of planned agriculture (Heinsalu and Veski, 2010). Agriculture in Karelia according to Hannula (2006), has been the permanent source of income from the 13th century onward. During WWII, Karelia, a previously Finnish province was ceded to the Soviet Union and therefore agriculture ceased. (Hannula, 2006). The area around the lake, experienced a reduction in slash and burn cultivation by 40 BP which is also represented in the pollen spectra. By 1940s or 10 BP, the cultivation seems to have gone into a major cessation with *Cerealia* pollen almost disappearing suggesting that during the war years (1940 to 1944), cultivation was limited in the area (Miettinen et al. 2005) and almost abandoned.

From a climatic perspective, according to Andreev et al. (2002), a cooling trend occurred at 500 to 200 cal BP. This cooling, which perhaps corresponds to the Little Ice Age (LIA), is also noted by Väliranta et al. (2007) to have taken place between 350 and 30 BP in Finland. The LIA is the coldest episode recorded in late-Holocene lasting from 500 to 100 cal BP and is presented in the pollen spectra. *Chenopodiaceae* as discussed grows best in semi-arid cool regions and the A/C (*Artemisia*/*Chenopodiaceae*) pollen ratio can be a good indicator of humidity. The early abundance of *Chenopodiaceae* during the start of Zone C and its high peak at 300 cal BP indicate favorable dry climate for this taxon. However, the sudden decline in the *Chenopodiaceae* population at 230 cal BP implies a wet period that also boosted *Poaceae* cultivation by means of providing adequate moisture. This perhaps points to a humid LIA during this period around Lavijärvi, though LIA is known to have had shifting dry-wet periods (Chen et al. 2006) which is also obvious in the following *Chenopodiaceae* expansion. The decrease in *Chenopodiaceae* at ~200 cal BP coincides with low *Alnus* pollen. This is due to the warm-loving nature of *Alnus* and the effect of the LIA on the decline of this species. Perhaps, the most evident LIA effect, the decrease in almost all species (except for *Chenopodiaceae*), took place during the Maunder Minimum which occurred between 235 to 305 cal BP (Huhtamaa and Helama, 2017). The decrease in *Pinus*, *Betula*, *Alnus*, *Picea*, *Isoetes* and a steady state for *Poaceae* all suggest harsh climatic conditions that impacted the environment and prohibited the development of such taxa. The exceptional increasing state of *Chenopodiaceae* possibly leads to the fact that the LIA was somewhat dry during the Maunder Minimum and promoted *Chenopodiaceae* expansion. Another indicative reason that yields to the limited *Cerealia* cultivation and *Chenopodiaceae* advancement in this period is the escalated crop failure frequencies during the Maunder Minimum due to lasting cool summer temperatures. This failure provided suitable environment for farm desertion (Holopainen and Helema, 2009) and, therefore, serving as a convenient ground for *Chenopodiaceae* growth. From 235 BP onward, the temperature takes on an increasing trend and the weather becomes warmer and perhaps wetter providing adequate circumstances for expansion of *Alnus*, *Poaceae* and *Cerealia.* The wetness possibly decreased after a while as seen by the repeated expansion of *Chenopodiaceae* and decreasing *Poaceae* population.

The *Isoetes* community, as mentioned in the previous paragraphs begin by a rising progression at the commencement of Zone C. This trend agrees well with crop cultivation apparent in the diagram and suggest an excessive nutrient input for the lake by the transportation of organic matters from the cultivated soils to the lake system and advancement of organism and algae growth resulting finally in eutrophication. The eutrophication as explained before is well visible in the *Isoetes* expansion. The Quillworts (*Isoetes*) experience a decline at the period of Maunder Minimum. This can possibly be explained by the depletion of organisms due to the colder temperatures and therefore a less eutrophicated lake. Davydova and Servant-Vildary (1996), also describe that the lakes in northwestern Russia became oligotrophic during the Little Ice Age. After the LIA, with the onset of higher temperatures, *Isoetes* begin to rise again experiencing fluctuations throughout the rest of the core. These fluctuations are perhaps caused by the cultivation method variations along with LIA leftover effects impacting the environment.

To sum up, extreme fluctuation in *Pinus* and *Betula* population together with a distinct rise in *Chenopodiaceae*, *Poaceae* and *Cerealia* are among the features of Zone C. This zone experiences a major shift in landscape view from a coniferous-deciduous forest to a more steppe-forest vegetation. The Goosefoot heathlands with extensive crop cultivation takes place effectively in this period. The *Isoetes* community shows a change from constantly eutrophicated lake to fluctuating trophic status even experiencing a small oligotrophic status in LIA. Except for the limited Little Ice Age effects and temperatures, the climate seems to have been mainly warm and dry much like today's conditions with exceptional episodic rather high precipitation during the LIA. The world war effects such as cessation in *Cerealia* cultivation is also visible in the 1940s. It is worth mentioning that during the 20th century the slash and burn cultivation was replaced by arable farming and hence less fire frequencies (Alenius et al. 2004).

Zone D (10 to -66 BP or 1940 to 2016 AD): Zone of post war land relaxation

Zone D extends from 10 cal BP (1940 AD) until the end of the dated core -66 BP (2016 AD), and thus presents the most recent 76 years. During these years, with the termination of WWII, the land experiences a rather stress-free relaxation season and forest vegetation gradually take over the landscape in the lake's surroundings. By 1950s, *Pinus* experiences its highest peak throughout the whole pollen spectra reaching 60%. Though it decreases afterwards, it remains at a mean of above 40% thereafter. *Picea* after a 650 years hiatus makes a marking presence and takes on an ascending trend reaching about 15% by 2015. The steady high *Pinus* population along with the reappearance of *Picea* suggests less disturbance, e.g., fire in the area and abandonment of intensive cultivation. Though small-scale cultivation is still seen by the presence of *Poaceae*, it is assumed that arable farming and pasture has replaced the intensive slash and burn cultivation, which indicates less fire and adequate grounds for *Picea* growth. *Betula* remains high ~20% and together with high *Pinus* and *Picea* population, implies steady mixed coniferous-deciduous forest taking place once again. *Alnus* is also apparent taking small peaks suggesting warm temperatures (recent global warming?). The herb taxa of *Chenopodiaceae* after an abrupt cessation at ~1950s, perhaps due to land abandonment and less frequent cultivation, increases visibly and, along with the other tree taxa, illustrates slight openings in the mixed forest landscape. *Poaceae* pollen as discussed continues to be present with clear up and downs hinting small scale cultivation. The interruption in *Poaceae* along with the high population of *Chenopodiaceae* can perhaps also be rooted in recent global warming trends and less abundance of adequate moisture for its growth. The *Isoetes* become much less frequent but still present, proposing a less eutrophicated lake. The small-scale eutrophication status of the lake after the 1940s is also reported by Miettinen et al. (2005). The forest recovery and clear declination of cultivation during the late 20th century and early 21st century is also pointed out by Alenius et al. (2004). Overall, in the recent years the surroundings of Lake Ladoga and Lavijärvi represent succeeding recovering mixed coniferous-deciduous forest with small openings and pasture (Alenius et al. 2004) with a moderate-continental climate with mean annual precipitation of 650 to 700 mm and belong to the middle-southern boreal vegetation zone (Wohlfarth et al. 2001). At the very end of the core, the increasing Birch, Pine, Alder and Spruce trees indicate a relaxed land trying to regain its natural forest state after a long history of fluctuations and mixed forest to steppe-forest vegetation.

Though the focus of this thesis is on the pollen analyses of Lake Lavijärvi, a brief discussion of geochemical indicators will be presented in the upcoming section as well.

5.2. Geochemical and other indicators

Along the geochemical analyses done on Lake Lavijärvi sediment core (LAV16-05) are, assessment of grain size distribution, water content of the core and measurement of Total Nitrogen (TN), Total Inorganic Carbon (TIC), Total Organic Carbon (TOC), Total Sulfur (TS) and C/N ratio (Carbon to Nitrogen ratio).

Lake Lavijärvi's sediment core (LAV16-05), consists mainly of high silt grains (averaging at ~78%) with fluctuating sand (though always <10%) proportions and elevating clay levels toward the oldest part of the core (figure C in appendices). This would indicate a silt loam sediment with fine grains which allows water to penetrate the ground (Massa et al. 2012) and results in semi-saturation of the soil. This is also well visible in appendices figure D, where water content of core LAV16-05 seems to take a steady average of >60%.

The TN, TS and TIC measurements of core LAV 16-05 remain <1% or 0 (as is the case for TIC) all along the core (figures 11 and 12). Therefore, it can be estimated that during the time window of core LAV16-05, the surroundings of Lavijärvi were mostly semi-fertile soils, since both TN and TS are indicators of soil fertility and are greatly influenced by land-use, their absence and low content would generally represent an infertile or semi-fertile environments respectively (Wang et al. 2009). Though, as presented in the next section, the cultivated plants do not fail to grow on the site. The low amounts of TN and TS however tend to increase (experiencing small ups and downs) from the beginning of the core upward (figure 12). This would illustrate that at the commencement of the core or Zone A, the low TN (TN average: 0.197%) indicate a relaxed land with small or no cultivation taking place. Other than being signs of a relaxed forest, the low TN and TS of the sediment represent water quality of the lake as well, since TN and TS are also correlated with lake productivity (Wang et al. 2009). Therefore, we also see a non-eutrophicated lake with good productivity status as represented in Zone A (minimal Quillworts population). In Zone B, The TN and TS take on an ascending trend (TN average: 0.264%) which indicates that the forest is turning to grasslands (Wang et al. 2009) and cultivation is starting to take place relatively. Warming temperatures has also been associated with increasing Nitrogen sequestration (Marty et al. 2017) and therefore, the higher TN level of Zone B could perhaps be related to the Medieval Warming Period. Though cultivation is taking place firmly in Zone C, the TN and TS decrease slightly (TN average: 0.236%). This perhaps can be explained by the occurrence of the LIA in Zone C and the cooling climate conditions could have impacted the nutrients in soil. The fluctuating trophic status of the lake is also evident in Zone C and in the LIA, which further correlates with lowering TN and TS measurements. By Zone D, the TN and TS once again take on an increasing trend (TN average: 0.346%). This increment, however, do not correlate well with pollen and trophic status of the lake since the eutrophication of the lake is decreased by this zone and pastural activities are taking place and arable farming is becoming minimal. Perhaps reworking or contamination of sediment could be a reason of this increment. Though Franzluebbers and Stuedemann (2009ä) argue that pasture and grazing activities can indeed cause higher soil Nitrogen. TOC and C/N ratio are among other indices measured in geochemical analyses. The TOC of the sediment has an average of 2.570% throughout the LAV16-05 core while TIC is constantly 0.The high TOC levels from about 55-82 cm also correlate well with the eutrophication of the lake as seen in the pollen diagram. The increasing trend of TOC in the last part of the core (from ~8 cm onward) which represent approximately the recent 60 years is also reported by Miettinen et al. (2005). They explain that the organic material increases about 7% in recent sediments which agrees well with the increasing TOC levels of LAV16-05 sediment core's recent measurements.

The TOC, however, seems to remain high in early stages of human impact beginning in late Zone B and C. This can perhaps be explained by transportation of terrigenous stable organic residues from surface soils to the lake, whereas in later cultivation and human impact episodes, the eroded soil materials are less rich in organic material and presumably come from the deeper soil levels near bedrock (Oldfield et al. 2003). The increasing TN and TOC at the recent part of the core may suggest weakening of stratification and enhanced productivity. These along with the growing levels of organic material, hint to expansion of soils and vegetation in the lake catchment and illustrate a warming climate (Massa et al. 2012), perhaps an indicator of recent global warming trends.

The rising levels of C/N in lake sediments usually determine phases of large terrigenous input, though human land-use and impact might cause contradictory levels of C/N in lakes (Enters et al. 2006). The C/N level of core LAV16-05 seems to have been regularly stable with an average of 10.87, however, at around 23.5-20 cm a noticeable peak (18.18, 16.10,17.27 and 15.42) is displayed. This coincides with minimum *Pinus* pollen and the period of strong land-use and cultivation (*Cerealia* pollen present). This peak of C/N can perhaps be explained by the human land-use and *Pinus* declination, since the C/N is known to increase in areas where human settlement, impact and deforestation cause higher amounts of organic material being deposited in the lakes (Enters et al. 2006). This C/N increase at the end of Zone C also well corelate with the establishment of arable farming in the early 20th century and thus more water runoff resulting in an increment of sediment flux into the lake. The normal C/N levels at other depths of the core, can also be rooted to elevated aquatic production as seen by the aquatic vegetation enhancement in the pollen diagram (Enters et al. 2006). In short, though C/N is a reliable indicator of human-impact it can also be misdirecting as sometimes this ratio does not correspond with land-use effects and has contradictory levels. Therefore, it is important and necessary to crosscheck C/N values with other data or available proxies in order to be sure of what they actually imply.

Chapter 6: Conclusion

In recent years, while trying to find ways to understand global warming and climate change, the study of paleoclimate and paleoecology has advanced since they bring new information about past vegetation and climate patterns to the table. These information can be quite useful since the past is a key to understand the future. As a part of the Paleofarm project of Eawag institute, fossil pollen were extracted from Lake Lavijärvi (sediment core LAV16-05) situated in west Karelian Russia and illustrated the recent ~3000 years of vegetation cover and changes of the lake's surroundings. The core was dated by means of ^{210}Pb and ^{14}C and the samples were treated geochemically for the preparation of pollen. The pollen were counted and identified using a pollen guide from University of Bern and about 21 pollen and spore types were identified. Deciding by the major vegetation pattern changes, the pollen diagram was divided into 4 zones. The early stages of vegetation cover of Lavijärvi's surrounding (Zone A) consist of an above 80% forest view with *Pinus* and *Betula* dominating the forest. *Picea* is visibly present throughout this period which suggest a stress-free mixed conifer-deciduous forest with minimal fire episodes and almost no cultivation. This zone represents a consistent arboreal forest with limited herb taxa present, suggesting a climate favorable for the dominant species. The climate was perhaps experiencing more precipitation than today with adequate snow cover in winters (this is admitted by the continuous presence of *Picea* which need excessive snow cover to protect its seed). Zone B or zone of transition to forest-steppe vegetation progress with the arboreal trees declining and *Picea* taking on a decreasing trend. This along with the increasing herb species and initial land-use indicator plants, show a shift in vegetation cover and appearance of early cultivation. Noticeable eutrophication of the lake is visible with the strong presence of *Isoetes*. This era is represented by enough soil moisture, hence the growth of *Poaceae* and a warming trend toward the end of Zone B, possibly as a sign of the Medieval Warm Period. Zone C, a zone of major fluctuations in the vegetation pattern, experiences sudden changes of vegetation and a significant rise in herb plants. This zone offers extensive cultivation plans of the land with supporting edible taxa such as wild goosefoot being present. The number of arboreal trees vary but remain lower than overall herb species suggesting open landscape used for farming and slash and burn cultivation. The trophic status of the lake also changes frequently during this period indicating signs of less abundant nutrients (perhaps the Little Ice Age effect). The temperature is assumed to have been mostly dry due to strong presence of *Chenopodiaceae* plant though still enough soil moisture was available for cultivated plants. Towards the end of Zone C, the cessation of *Cerealia* cultivation as a result of land abandonment and ending of World War II is apparent along with lower levels of lake eutrophication and a rising trend for arboreal trees. The pollen diagram ends with Zone D or the zone of land relaxation. Other geochemical analyses done on the sediment core also reveal useful information regarding the organic matter levels of the lake hinting to existence of steady levels of TOC, TN and TS and absence of inorganic carbon. In-addition, the grainsize indicators represent a silt loam sediment profile that is well able to absorb water and displays a semi-saturated sediment. All in all, after centuries of land cultivation, Lavijärvi's surroundings seem to have shifted to more pasture-like fields with coniferous and deciduous forests beginning to repopulate the area and arable farming replacing slash and burn cultivation.

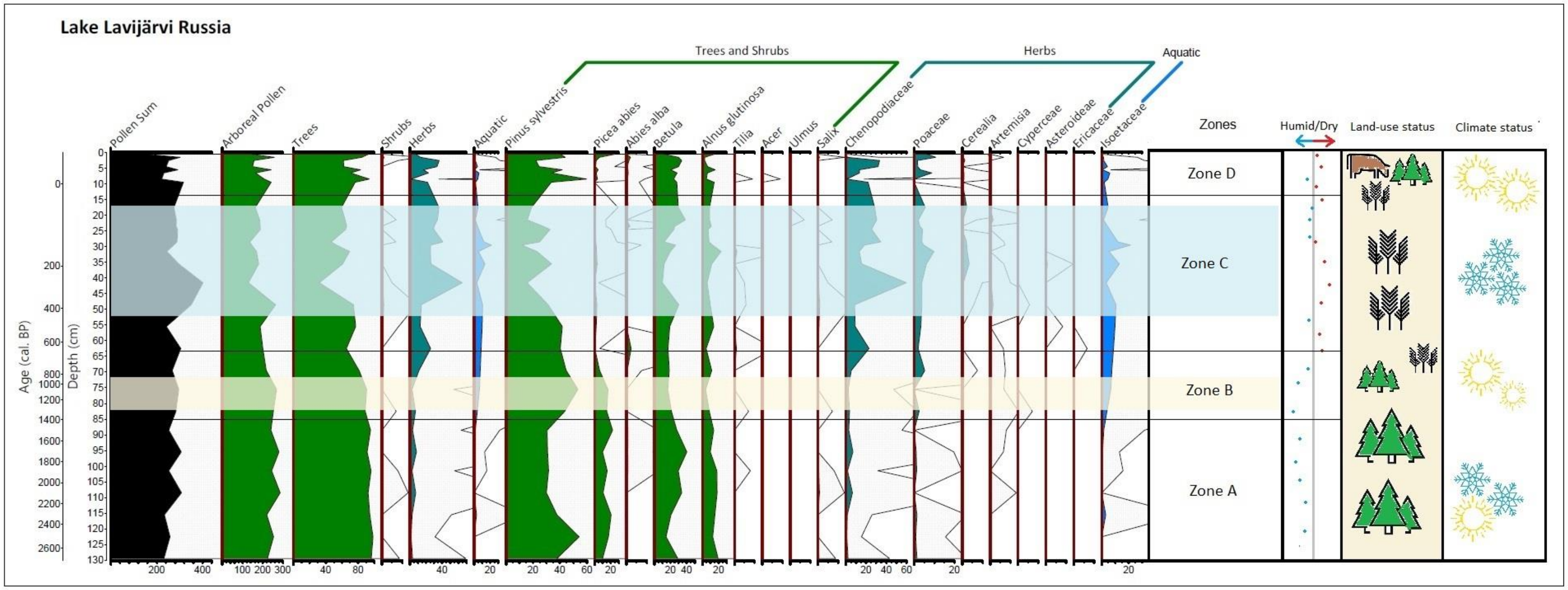

Figure 15: The pollen diagram of Lake Lavijärvi along with descriptive columns about humidity level, land-use and climate status. The barley, animal and pine symbols represent cultivation, pasture and forest/land relaxation respectively. The sun and snowflake symbols represent cool and warm climate, respectively. The horizontal highlighted blue and yellow sections display the Little Ice Age and Medieval Warm Period respectively. All descriptive figures were drawn relatively.

Acknowledgments

Achieving every milestone in life requires a significant amount of time, energy and more importantly, the help and advice of those who support you. I would like to sincerely thank my supervisor, Prof. Dr. Nathalie Dubois. I appreciate the opportunity she gave me to conduct my Master's research project with her and I am forever grateful for having the chance to learn life-improving lessons and collaborate with such an inspirational woman and her team. Without her advice and support this work would have not been possible to do. I am also thankful toward my Master's advisor Prof. Dr. Antti Lauri. Through my Master's years, he was an attentive, kind and supportive advisor who helped me find a solution to all the challenges and I am grateful for his endless guidance, especially with my thesis work. I would like to thank my friend Mischa Haas who, with a pleasant smile, always helped me with scientific details of this work and gave me insightful advice. His help and prompt responses to my many questions will always be appreciated. I like to thank Dr. Erika Gobet at Plant Institute of the University of Bern and Ms. Irene Brunner at Sedimentology Laboratory of Eawag Institute for their help with the lab work and experiments.

I would also like to thank my friend Michele in Helsinki for helping with my pollen analysis questions and for her positive energy! Faeze, my dearest wonderful best friend. Without your unequivocal emotional support, I wouldn't have made it through. Dear Asiye, thank you for sharing your home with me and being a true friend, I will never forget your heart-warming kindness.

Last but definitely not least, I would like to dedicate this work to my family. My dear Mohammad Hossein, thank you for accompanying me through these years, I am forever grateful. My brothers, Mohammad, Mostafa and Hossein. I followed along your footsteps in life and I am proud to have done so as you encourage me to follow my dreams every day, thank you for always believing in me. And finally I would like to thank my parents. Words are not enough to show my gratitude for what you have given me in life. Dad, you inspire me every day to conquer my fears, you encourage me to use all my potential, and you reassure me that with hard work, dedication and hope everything is possible. You are the most inspiring person in my life. Mom, thank you for your compassion. For teaching me to always be curious in life and to learn from my mistakes. Thank you for your never-ending love and kindness. I love you. And thanks to all who helped me along the way.

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Appendices

						Time Info		
Core	*Nr.*	*From*	*To*	*Length (cm)*	*From (AD)*	*To (AD)*	*Time (y)*	
LAV16-05	a	0	65	65	2016	1760	256	
LAV16-05	b	65	137	72	1760	1477	283	
			Total:	137	cm	Total:	539	
Resolution:				**20**	Samples			
Take a sample every				**27**	y **6.85**	cm		
High Resolution at interesting Periods (WW2)								
Modern	1900 - 2016 - 10 additional samples				every	7	y	
Pollen sampling	*Sampling Position*			*Total Depth*		*Age Model Pb210 excess dating*		
Sample Nr.	*Core*	*From*	*To*	*From*	*To*	*AGE*	*Sedi-Rate [cm/y]*	*y/cc*
P-LAV_01	a	0	1	0	1	2013	0.15	6.67
P-LAV_02	a	1	2	1	2	2006	0.15	6.67
P-LAV_03	a	2	3	2	3	1999	0.15	6.67
P-LAV_04	a	4	5	4	5	1986	0.15	6.67
P-LAV_05	a	5	6	5	6	1979	0.15	6.67
P-LAV_06	a	6	7	6	7	1972	0.15	6.67
P-LAV_07	a	8	9	8	9	1959	0.15	6.67
P-LAV_08	a	9	10	9	10	1952	0.15	6.67
P-LAV_09	a	17	18	17	18	1945	0.25	4.00
P-LAV_10	a	21	22	21	22	1932	0.25	4.00
P-LAV_11	a	23	24	23	24	1925	0.25	4.00
P-LAV_12	a	24	25	24	25	1918	0.25	4.00
P-LAV_13	a	28	29	28	29	1905	0.25	4.00
P-LAV_14	a	29	30	29	30	1898	0.25	4.00
P-LAV_15	a	31	32	31	32	1891	0.25	4.00
P-LAV_16	a	35	36	35	36	1878	0.25	4.00
P-LAV_17	a	41	42	41	42	1851	0.25	4.00
P-LAV_18	a	48	49	48	49	1824	0.25	4.00
P-LAV_19	a	55	56	55	56	1797	0.25	4.00
P-LAV_20	a	62	63	62	63	1770	0.25	4.00
P-LAV_21	b	4	5	69	70	1743	0.25	4.00
P-LAV_22	b	11	12	76	77	1716	0.25	4.00
P-LAV_23	b	18	19	83	84	1689	0.25	4.00
P-LAV_24	b	24	25	89	90	1662	0.25	4.00
P-LAV_25	b	31	32	96	97	1635	0.25	4.00
P-LAV_26	b	38	39	103	104	1608	0.25	4.00
P-LAV_27	b	45	46	110	111	1581	0.25	4.00
P-LAV_28	b	52	53	117	118	1554	0.25	4.00
P-LAV_29	b	59	60	124	125	1527	0.25	4.00
P-LAV_30	b	66	67	131	132	1500	0.25	4.00

Table 1: The pollen sampling strategy based on the ^{210}Pb dates derived from the gamma radiation measurements. Sedimentation rates (cm/y) is also shown according to the ^{210}Pb age model.

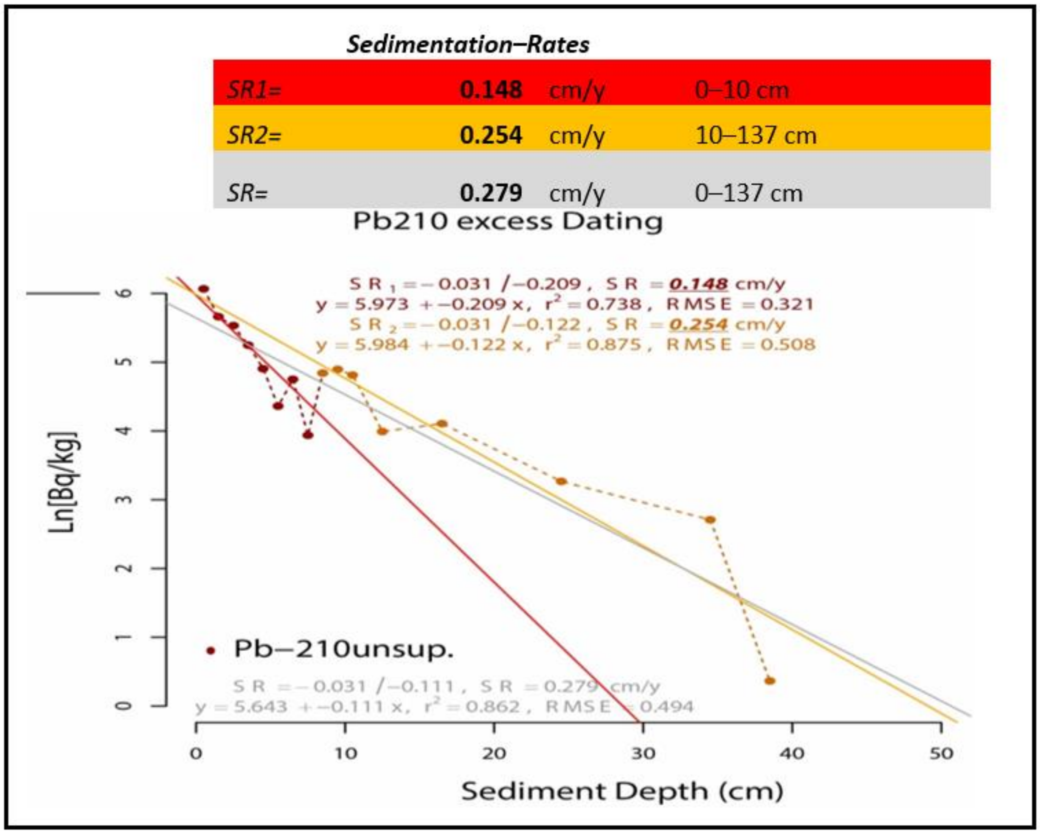

Figure A: The unsupported ^{210}Pb excess dating graph, showing the sedimentation rates of the different depths of Lavijärvi (credit: Mischa Haas)

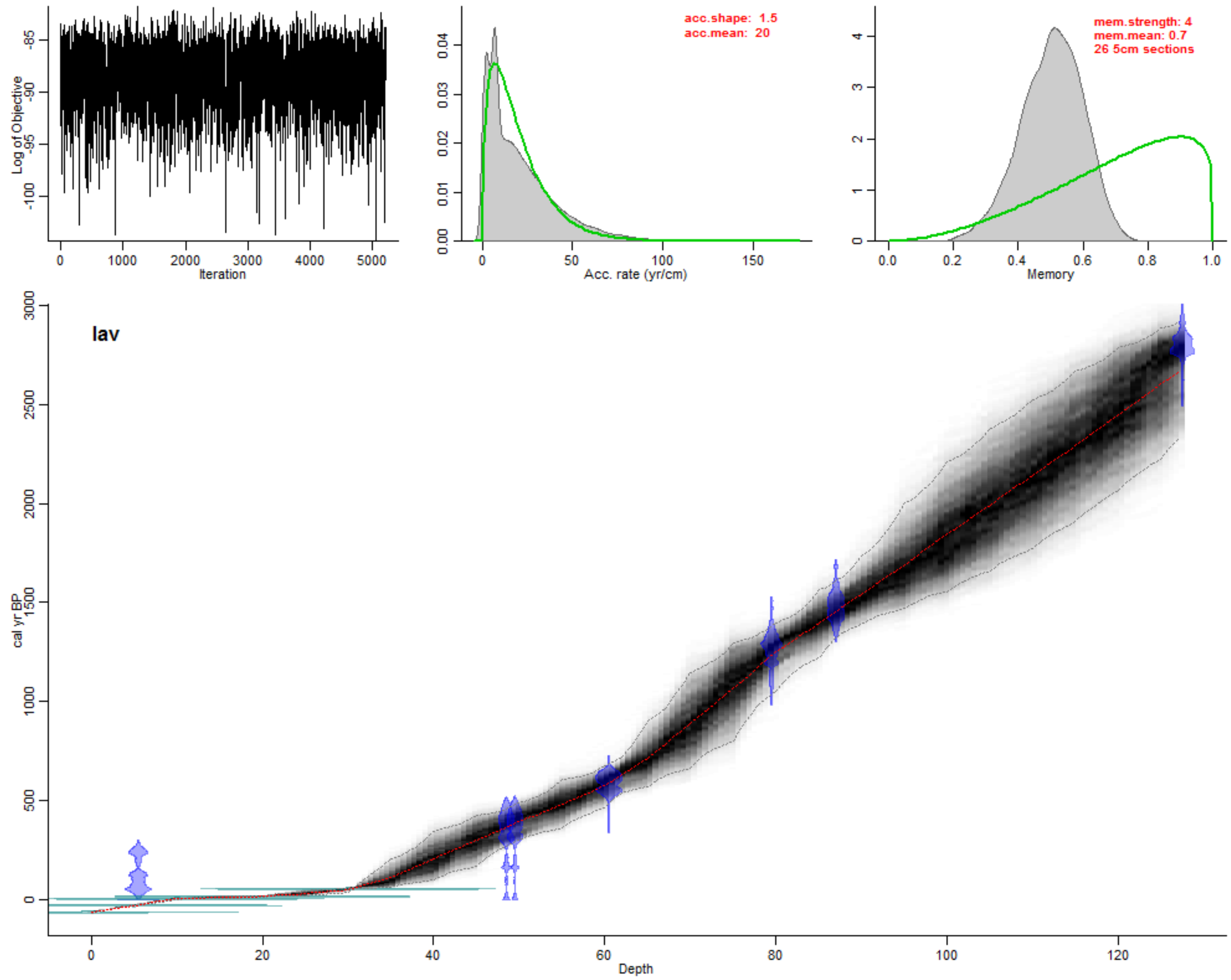

Figure B: The Bayesian age-depth model of LAV16-05 according to the [14]c dates. The dates of this model was used in the pollen diagrams (credit: Mischa Haas)

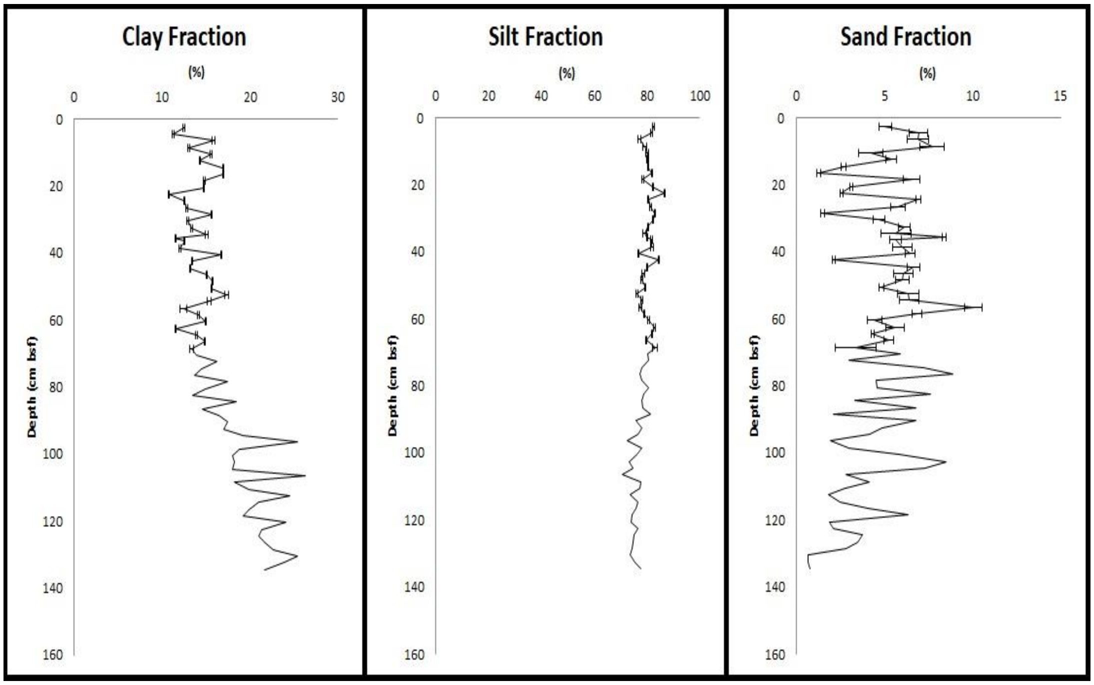

Figure C: The downcore grain size distribution of core LAV16-05

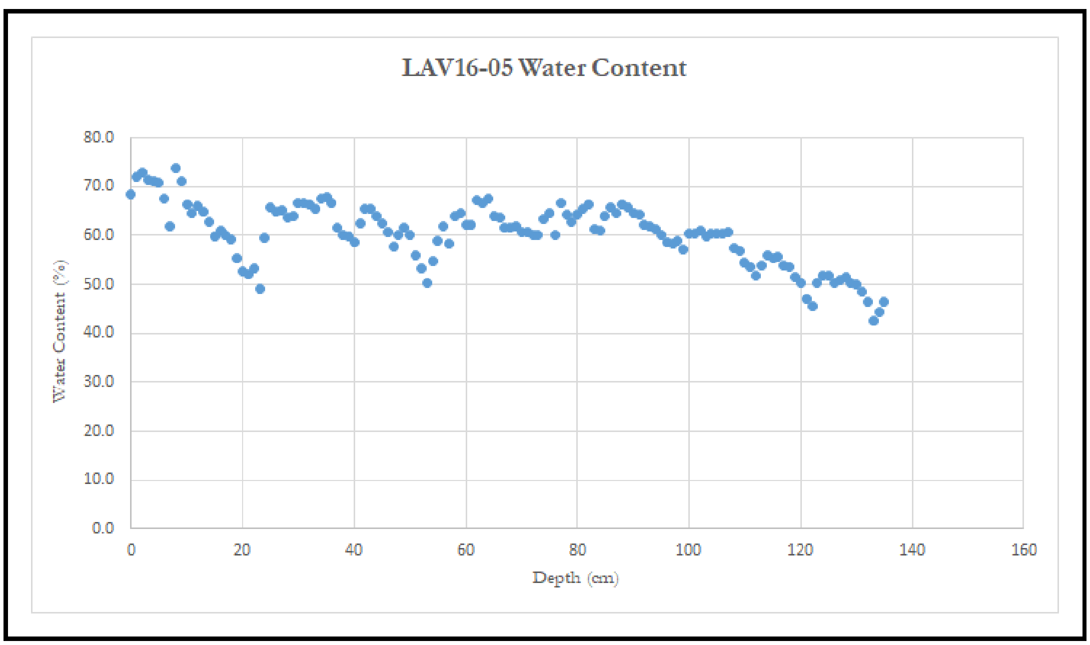

Figure D: The water content of core LAV16-05